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DEVELOPMENT OF LATERAL-DIRECTIONAL TRANSFER FUNCTIONS FOR CLASS IV AIRCRAFT WITH LEVEL 1 FLYING QUALITIES

Julieta E. Booz
Air Vehicle Department (Code 432300R08)
NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
WARMINSTER, PA 18974-0591

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Prepared for:
M. Steinberg
Air Vehicle Department (Code 432400R08)
Naval Air Warfare Center Aircraft Division
Warminster, PA 18974-0591

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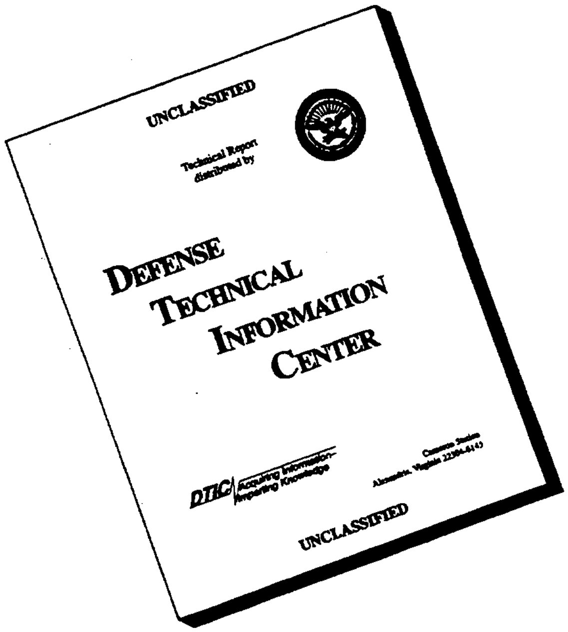

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This report describes the computer program that was developed to support the effort currently being conducted at C. S. Draper Laboratory, Inc. to develop a hybrid, learning augmented, lateral-directional flight control system. The output from the computer program is a set of transfer functions for trimmed flight conditions which can be used to describe representative F-18 time histories. The transfer functions meet the Level 1 Flying Qualities Requirements of MIL-F-8785C for Flight Phase Categories A and B of the F-18's flight envelope. These include roll angle, roll rate, sideslip, yaw rate and lateral acceleration to lateral stick and pedal inputs. The computer program was written in Visual Basic and the coefficients to the transfer functions are written to an output file.

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SUMMARY

This report describes the computer program that was developed to support the effort currently being conducted at C. S. Draper Laboratory, Inc. to develop a hybrid, learning augmented, lateral-directional flight control system. The output from the computer program is a set of transfer functions for trimmed flight conditions which can be used to describe representative F-18 time histories. The transfer functions meet the Level 1 Flying Qualities Requirements of MIL-F-8785C for Flight Phase Categories A and B of the F-18's flight envelope. These include roll angle, roll rate, sideslip, yaw rate and lateral acceleration to lateral stick and pedal inputs. The computer program was written in Visual Basic and the coefficients to the transfer functions are written to an output file.

This report includes a description of the transfer function development, the computer program structure and input/output content and format. A sample application is also included to aid the user in understanding the program application.

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LIST OF SYMBOLS

A, B, C, D	Coefficients to transfer function
$a_{y_{cg}}$	Lateral Acceleration at the center of gravity (ft/sec^2)
b	Reference Wing Span (ft)
C_l, C_N, C_Y	Coefficient of Rolling Moment, Yawing Moment and Side Force
C_{l_β}	Coefficient of Rolling Moment with respect to sideslip, $\frac{\partial C_l}{\partial \beta}$
C_{n_β}	Change in Yawing Moment Coefficient with respect to sideslip, $\frac{\partial C_n}{\partial \beta}$
C_{y_β}	Change in Side Force Coefficient with respect to sideslip, $\frac{\partial C_l}{\partial \beta}$
C_{l_r}	Change in Rolling Moment Coefficient with respect to yawing velocity, $\frac{\partial C_l}{\partial \left({rb}/{2U} \right)}$
C_{n_r}	Change in Yawing Moment Coefficient with respect to yawing velocity, $\frac{\partial C_n}{\partial \left({rb}/{2U} \right)}$
C_{l_δ}	Change in Rolling Moment Coefficient with variation in control surface deflection, $\frac{\partial C_l}{\partial \delta}$
DLL	Dynamic Link Library
DOF	Degrees of Freedom
EOM	Equations of Motion
F_s, F_p	Lateral Stick and Pedal Force input (lbs)
g	Acceleration due to gravity (ft/sec^2)
H	High Speed Category
I_{xx}, I_{yy}, I_{zz}	Body Axis Moments of Inertia (slug-ft^2)
I_{xz}	Product of Inertia (slug-ft^2)
L	Rolling Moment (ft-lbs)
L	Low Speed Category
$L_{(\ )}$	$\frac{1}{I_{xx}} \frac{\partial L}{\partial (\ )}$
L_i'	$\frac{L_i + \left({Ixz}/{Ixx} \right) N_i}{1 - \left(I_{xz}^2 / I_{xx} I_{zz} \right)}$
L_{Fa}'	Roll to Lateral Stick Transfer Function Command Gain ($\frac{\text{deg/sec}^2}{\text{lb}}$)
m	Mass (slugs)
M	Medium Speed Category
N	Yawing Moment (ft-lbs)
$N_{\delta_{r,a}}^{(\ )}$	Numerator of the transfer function to rudder pedal or lateral stick input

$N_{( )}$	$\frac{1}{I_{zz}}\frac{\partial N}{\partial ( )}$
N_i'	$\frac{N_i + \left(I_{xz}/I_{zz}\right)L_i}{1-\left(I_{xz}^2/I_{xx}I_{zz}\right)}$
p, q, r	Body Axis Angular Rates (Roll, Pitch, Yaw) (rad/sec)
p_{ss}	Steady State Roll Rate (deg/sec)
s	Laplace Operator
S	Reference Wing Area (ft^2)
U	Body Axis Velocity in the X direction (ft/sec)
U_0	Initial Body Axis Velocity in the X direction (ft/sec)
V	Total Velocity (ft/sec)
VL	Very Low Speed Category
V_{max}	Maximum Service Speed (ft/sec)
V_{min}	Minimum Service Speed (ft/sec)
$V_{o_{max}}$	Maximum Operational Speed (ft/sec)
$V_{o_{min}}$	Minimum Operational Speed (ft/sec)
Y	Side Force (lbs)
$Y^*_{( )}$	$\frac{1}{mU}\frac{\partial Y}{\partial ( )}$
β	Sideslip Angle (rad)
$\delta_{a,s,r}$	Aircraft Aileron, Stabilator and Rudder Deflection (rad)
Δlat-dir	Denominator of the Lateral-Directional Transfer Function
ρ	Air Density (slugs/ft^3)
φ	Roll Angle (rad)
ψ	Yaw Angle (rad)
τ_R	Roll Mode Time Constant (sec)
τ_s	Spiral Mode Time Constant (sec)
ω_d	Dutch Roll Frequency (rad/sec)
ω_φ	Undamped Natural Frequency of Numerator Quadratic in φ / F_s Transfer Function Numerator (rad/sec)
ς_d	Dutch Roll Damping
ς_φ	Damping Ratio of Numerator Quadratic in φ / F_s Transfer Function Numerator

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l	Rolling Moment Parameter
n	Yawing Moment Parameter
p	Roll Rate Parameter
r	Yaw Rate Parameter
v	Body Axis y-Velocity Parameter
y	Side Force Parameter
β	Sideslip Parameter
δ_a	Aileron Deflection Parameter
δ_r	Rudder Deflection Parameter
δ_s	Stabilator Deflection Parameter
φ	Roll Angle Parameter

1.0 INTRODUCTION

C. S. Draper Laboratory, Inc. is currently conducting a research program to design, develop and evaluate a hybrid, learning augmented, lateral-directional flight control system for a nonlinear aircraft model of the F-18. This effort is to support the technology program entitled "Aircraft Vehicle Technology Block", Section 8.0, "Dynamics of Flight", Task Area 8.4, "Advanced Flight Controls". The control system performance will be tested against a linearized reference model representative of the F-18 with Level 1 lateral-directional flying qualities throughout the flight envelope. The reference model will provide Level 1 transient responses to stick and pedal inputs. This report describes the approach, basic assumptions, and the computer code used to develop the reference model.

2.0 APPROACH

The objective of this effort was to develop a lateral-directional reference model that would provide time histories that demonstrate Level 1 lateral-directional flying qualities throughout the flight envelope of the F-18 modeled at C. S. Draper Laboratory, Inc. The approach taken was to provide simplified transfer functions through pole-zero placement that are representative of the F-18. The simplified transfer functions were designed to meet the Level 1 lateral-directional flying qualities requirements outlined in MIL-F-8785C (Reference 1) for Flight Phase Categories A and B. Only those requirements which could be represented by transfer functions were addressed in this effort. The reference transfer functions were then used to generate the required time histories to different stick and pedal inputs at any trimmed flight condition. For simplification it was assumed that the reference model could be represented by the classical lateral-directional 3 degree-of-freedom (DOF) equations of motion (EOM), as described in Reference 2. With this assumption there was no coupling between the longitudinal EOM and the lateral-directional EOM. By using the classical lateral-directional 3 DOF EOM, the modal characteristics and the resulting transfer functions were described purely by the roll mode time constant (τ_R), the spiral mode time constant (τ_s), and the Dutch roll frequency (ω_d) and damping (ς_d).

The poles or the modal characteristics of the transfer functions were taken from Reference 3 as a function of Mach and altitude. In those instances where the modal characteristics do not meet the Level 1 Flying Qualities Requirements of MIL-F-8785C, the values were modified to the appropriate maximum or minimum values. This was based on the assumption that the new control system would augment the F-18 model dynamics to meet MIL-F-8785C requirements. For simplification the spiral mode time constant was set to zero throughout the flight envelope. Although most of MIL-F-8785C requirements could be satisfied through the roll response to lateral stick force transfer function, the intent of this effort was to provide multiple Level 1 reference time histories for the hybrid lateral-directional flight control system. The transfer functions gains and zeros were either placed or calculated to provide Level 1 Flying Qualities. The values for the numerator gains and zeros depended on the transfer function being evaluated. The following paragraphs will describe how these transfer functions numerators and gains were computed.

2.1 ASSUMPTIONS

This section presents the basic assumptions used to simplify the equations of motion in order to generate the transfer functions calculated by the computer program (F18LDTF). These are standard assumptions as applied in Reference 2.

Assumption 1.	The airplane is assumed to be a rigid body.
Assumption 2.	The earth is assumed to be an inertial frame of reference.
Assumption 3.	The mass and mass distribution of the airplane are assumed to be constant.
Assumption 4.	The XZ plane is assumed to be the plane of symmetry.
Assumption 5.	The disturbances from the steady flight conditions are assumed to be small enough that the small angle approximations are applicable.
Assumption 6.	The steady lateral trim conditions are assumed to be such that initial roll (p) and yaw (r) rates, roll angle (φ) and sideslip angle (β) are zero and the longitudinal forces and moments due to lateral perturbations about such trim conditions are assumed negligible.
Assumption 7.	The air flow is assumed to be quasi steady.
Assumption 8.	The variation of atmospheric properties such as density are assumed to be negligible.
Assumption 9.	The earth is assumed to be flat such that the effects associated with the rotation of the vertical axis of the airplane while moving in the inertial frame are assumed negligible. In addition the airplane is trimmed for straight and level flight with pitch rate (q) = 0
Assumption 10.	The equations of motion are based on a stability axis system.
Assumption 11.	In the steady flight condition, the flight path of the airplane is assumed to be horizontal.

In addition the following auxiliary relationships were applied:

$$p = \dot{\varphi} \tag{1}$$

$$r = \dot{\psi} \tag{2}$$

$$a_{y_{cg}} = U_0\dot{\beta} - g\varphi + U_0 r \tag{3}$$

2.2 DERIVATION OF THE EQUATIONS OF MOTION

The assumptions and auxiliary equations cited in the previous section permits the decoupling of the longitudinal and lateral-directional EOM. In addition the 3-DOF Dutch roll approximation was applied since it complemented the assumption that $\tau_s = 0$ throughout the flight envelope. The assumptions used in the 3-DOF Dutch Roll approximations are:

Assumption 12.	The rolling acceleration due to yaw rate, $L'_r r$, is negligible.
Assumption 13.	The yawing acceleration due to roll rate, $N'_p p$, is negligible.
Assumption 14.	The contribution of gravity term to the side force equation, $\frac{g\varphi}{U_0}$, is negligible.

The resulting equations for the F-18 modeled in the computer program are as follows:

$$(s - Y_v)\beta(s) \qquad + r(s) \qquad = (Y^*_{\partial_a})\delta_a(s) + (Y^*_{\partial_s})\delta_s(s) + (Y^*_{\partial_r})\delta_r(s) \tag{4}$$

$$-L'_\beta\beta(s) + s(s - L'_p)\varphi(s) \qquad = (L'_{\partial_a})\delta_a(s) + (L'_{\partial_s})\delta_s(s) + (L'_{\partial_r})\delta_r(s) \tag{5}$$

$$-N'_\beta\beta(s) \qquad + (s - N'_r)r(s) \qquad = (N'_{\partial_a})\delta_s(s) + (N'_{\partial_s})\delta_s(s) + (N'_{\partial_r})\delta_r(s) \tag{6}$$

The transfer functions were obtained by solving the Laplace transformed perturbation equation for the output variable of interest with all other inputs considered to be zero. The equations for the lateral-directional responses to controller inputs were defined as follows:

$$\beta(s)/\delta(s) = (A_\beta\, s + B_\beta)/\Delta\text{lat-dir} \tag{7}$$

$$r(s)/\delta(s) = (A_r\, s + B_r)/\Delta\text{lat-dir} \tag{8}$$

$$\begin{aligned}\varphi(s)/\delta(s) &= (A\varphi\, s^2 + B\varphi s + C\varphi)/\Delta\text{lat-dir}\\ \text{or} &= A_\varphi(s^2 + 2\varsigma_\varphi \varsigma_d \omega_\varphi s + \omega_\varphi{}^2)/\Delta\text{lat-dir}\end{aligned} \tag{9}$$

$$p(s)/\delta(s) = s(A\varphi\, s^2 + B\varphi s + C\varphi)/\Delta\text{lat-dir} \tag{10}$$

$$\begin{aligned}\Delta\text{lat-dir} &= s(As^3 + Bs^2 + Cs + D)\\ \text{or} &= s(s + 1/\tau_R)(s^2 + 2\varsigma_d \omega_d s + \omega_d{}^2)\end{aligned} \tag{11}$$

where:

A, B, C, D = coefficients of the transfer functions
Δlat-dir = denominator of the transfer function .

The roll angle, roll rate and sideslip response to aileron command (φ/δ_a, p/δ_a, and β/δ_a respectively) were defined by pole-zero placement to meet the Level 1 lateral-directional flying qualities requirements of MIL-F-8785C. This was done by using F-18 data (Reference 3) to define the denominator of the transfer function and set the numerator zeros and gains to satisfy MIL-F-8785C. The remaining transfer functions were defined from F-18 aerodynamic data from Reference 4. Table 1 provides the coefficients for the numerators of the transfer functions in terms of the primed dimensional stability derivatives as defined in Reference 2. In addition many of MIL-F-8785C requirements are stated in terms of responses to lateral stick force or pedal force inputs. In order to model the transfer functions as responses to force inputs, simplified linear relations between force inputs and control deflections were derived and applied as a gain to the transfer functions. By using this method the roll and yaw contributions due to the stabilator were combined with the aileron inputs to yield the yaw rate response to lateral stick force inputs.

TABLE 1
LATERAL-DIRECTIONAL NUMERATOR TRANSFER FUNCTION COEFFICIENTS

	A	B	C
$N^\beta_{\delta_r}$	$Y^*_{\delta_r}$	$Y^*_{\delta_r}(-N'_r - (N'_{\delta_r}/Y^*_{\delta_r}))$	
$N^r_{\delta_r}$	N'_{δ_r}	$N'_{\delta_r}(-Y_v + (Y^*_{\delta_r}/N'_{\delta_r})N'_\beta)$	
$N^\varphi_{\delta_r}$	L'_{δ_r}	$L'_{\delta_r}(-Y_v - N'_r + (Y^*_{\delta_r}/L'_{\delta_r})L'_\beta)$	$L'_{\delta_r}\left(N'_\beta\left(1 - \frac{L'_\beta N'_{\delta_r}}{L'_{\delta_r}N'_\beta}\right) + Y_vN'_r - (Y^*_{\delta_r}/L'_{\delta_r})L'_\beta N'_r\right)$
$N^r_{\delta_a}$	N'_{δ_r}	$N'_{\delta_a}(-Y_v + (Y^*_{\delta_a}/N'_{\delta_a})N'_\beta)$	
$N^r_{\delta_s}$	N'_{δ_s}	$N'_{\delta_s}(-Y_v + (Y^*_{\delta_s}/N'_{\delta_s})N'_\beta)$	

2.3 MODAL CHARACTERISTICS

The modal characteristics are defined as the roots of the characteristic equation of the transfer function denominator. Equation (11) describes the modal characteristics of the reference model used in this computer code and was used to satisfy the following MIL-F-8785C requirements:

3.3.1.1 Lateral-Directional Oscillations (Dutch Roll)
3.3.1.2 Roll Mode
3.3.1.3 Spiral Stability

As stated earlier the spiral mode time constant (τ_s) was set to zero throughout the flight envelope which meets the flying qualities specification requirement in MIL-F-8785C Paragraph 3.3.1.3 since τ_S is neutrally stable. The values for the remaining roots of the characteristic equation were from Reference 3 as a function of Mach and altitude to provide values representative of the F-18. The Dutch roll frequency and damping were tested against the specification minimum values of ω_d > 1.0 rad/sec and ς_d>0.4 (MIL-F-8785C Paragraph 3.3.1.1). If ω_d and ς_d did not meet the minimum values then the program set the data to those minimum values. If τ_R exceeded the maximum specification value of 1.0 seconds (MIL-F-8785C Paragraph 3.3.1.2) the program sets τ_R= 1.0. Although no minimum value is called out in the specifications, past experience (Reference 5) has shown that designers should avoid too low an augmented value for τ_R to prevent roll ratcheting. Since the F-18 by design has relatively low values for τ_R, a minimum of 0.3 seconds was selected to prevent potential roll ratcheting in the hybrid control system.

2.4 ROLL REQUIREMENTS

The roll angle and roll rate response to lateral stick force inputs were used to satisfy the following MIL-F-8785C requirements:

3.3.2.2 Roll Rate Oscillations
3.3.2.2.1 Additional Roll Rate Requirement For Small Inputs
3.3.2.3. Bank Angle Oscillations
3.3.4.1 Roll Performance for Class IV Airplanes
3.3.4.1.3 Roll Response
3.3.4.4 Linearity of Roll Response

The roll response to lateral stick force inputs (φ / F_s) and the roll rate response to lateral stick force inputs (p / F_s) were represented by the following equations:

$$\frac{\varphi}{F_s} = \frac{L'_{Fa}(s^2 + 2\zeta_\varphi \omega_\varphi s + \omega_\varphi^2)}{(s)(s + 1/\tau_R)(s^2 + 2\zeta_d \omega_d s + \omega_d^2)} \tag{12}$$

$$\frac{p}{F_s} = \frac{L'_{Fa}(s)(s^2 + 2\zeta_\varphi \omega_\varphi s + \omega_\varphi^2)}{(s)(s + 1/\tau_R)(s^2 + 2\zeta_d \omega_d s + \omega_d^2)} \tag{13}$$

where:

L'_{Fa} = command gain to stick force

To meet the roll oscillation requirement stated in paragraphs 3.3.2.2, 3.3.2.2.1, and 3.3.2.3 of MIL-F-8785C the complex roots of the numerator and denominator were canceled ($\omega_d = \omega_\varphi$ and $\varsigma_d = \varsigma_\varphi$). By

canceling the complex roots the Dutch roll mode was not excited and thus inherently satisfied the above requirements.

The resulting equation for the roll rate response was:

$$\frac{p}{F_s} = \frac{L'_{Fa}}{\left(s + 1/\tau_R\right)} \tag{14}$$

The term L'_{Fa} was then calculated from the steady-state roll equation (p_{SS}) where:

$$p_{ss} = L'_{Fa}(\tau_R)F_s \tag{15}$$

By rearranging Equation (15) the computer program solves for L'_{Fa} using Equation 16.

$$L'_{Fa} = \frac{p_{ss}}{\tau_R F_s} \tag{16}$$

The data for p_{ss} was taken from Reference 6, which contained data for predicted maximum steady state roll as a function of Mach and altitude. The lateral stick force input was modeled to reflect that for Class IV aircraft aileron effectiveness which is nonlinear with deflection (i.e. large deflections produce an incrementally larger rolling moment than do small deflections). This was achieved by modeling a nonlinear stick shaping curve within the region recommended in Reference 5 and is shown in Figure 1. Reference 5 indicated that designing within this region, excessive roll sensitivity can be avoided while maintaining adequate roll control power.

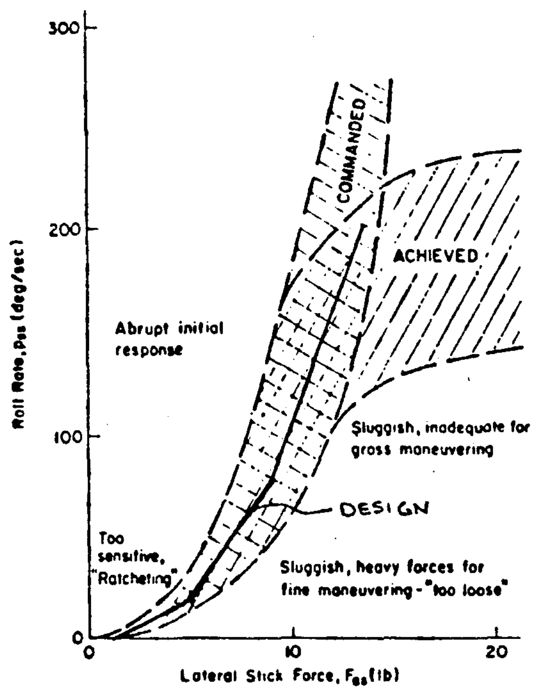


Figure 1. Design Roll Command Shaping

Paragraph 3.3.4.1 is a measure of time to change bank angle (φ) within a specified time as shown in Table 2. Table 3 contains the speed range definitions for Level 1 Class IV airplanes. Paragraph 3.3.4.1.3 states that "Stick-controlled Class IV airplanes in Category A Flight Phase shall have a roll response to roll control force not greater than 15 degrees in 1 second per pound for Level 1...". To meet paragraphs 3.3.4.1 and 3.3.4.1.3 of MIL-F-8785C L'_{Fa} is substituted into equation (12) since these two requirements are a function of roll or bank angle. The computer program calculates the roll response for the given time span and force input and tests the resulting values against the specification requirements for stick sensitivity and roll performance. If the value for L'_{Fa} did not satisfy those two requirements the value for L'_{Fa} was either increased or decreased so that the specification requirements were satisfied.

TABLE 2. LEVEL 1 ROLL PERFORMANCE FOR CLASS IV AIRPLANES FLIGHT PHASE CATEGORY A

TIME TO ACHIEVE THE FOLLOWING BANK ANGLE CHANGE (sec)

SPEED RANGE	30°	50°	90°
VL	1.1		
L	1.1		
M			1.3
H		1.1	

TABLE 3. LEVEL 1 AIRSPEED RANGE DEFINITIONS FOR CLASS IV AIRPLANES

SPEED RANGE SYMBOL	EQUIVALENT AIRSPEED RANGE
VL	$V_{o_{min}} \leq V < V_{min} + 20KTS$
L	$V_{min} + 20KTS^{(1)} \leq V < 1.4V_{min}$
M	$.4V_{min} \leq V < 0.7{V_{max}}^{(2)}$
H	$0.7{V_{max}}^{(2)} \leq V \leq V_{o_{max}}$

(1) or $V_{o_{min}}$ whichever is greater

(2) or $V_{o_{max}}$ whichever is less

The requirements of 3.3.4.4, Linearity of Roll Response would inherently be met by the low order representation of roll and roll rate transfer functions.

2.5 SIDESLIP REQUIREMENTS

The sideslip (β) response to lateral stick force input and rudder pedal force input was used to satisfy the following MIL-F-8785C requirements:

3.3.2.4 Sideslip Excursions
3.3.2.4.1 Additional Sideslip Requirement for Small Inputs
3.3.2.5 Control of Sideslip in Rolls
3.3.6.1 Yawing Moments in Steady Sideslips

Paragraphs 3.3.2.4, 3.3.2.4.1 and 3.3.2.5 were satisfied by assuming that the control system is capable of eliminating any sideslip generated by the lateral stick and basically setting the sideslip response to zero (0). An example procedure is outlined in Reference 5 that designs a stick crossfeed to the rudder pedals which would ideally eliminate the sideslip generated by the stick input.

Paragraph 3.3.6.1 was satisfied through the sideslip response to pedal force input (β/F_p) transfer function. In this effort the gain on the pedal to rudder deflection was set so that the right pedal (or positive input) would generate a left (or negative) rudder deflection and vice-versa.

The remaining transfer functions: roll and roll rate to pedal force input (φ / F_p and p / F_p), yaw rate to stick and pedal force inputs (r / F_s and r / F_p) and lateral acceleration at the center of gravity to stick and pedal force inputs ($a_{y_{cg}} / F_s$ and $a_{y_{cg}} / F_p$) were included as a matter of completeness but were not tailored to meet any specification requirements. The coefficients of the transfer functions were calculated as shown in Table 1. The equation for lateral acceleration at the center of gravity to stick and pedal inputs were computed according to Equation (3). Table 4 lists the equations for the dimensional stability derivatives and the primed derivatives used in Table 1. The non-dimensional stability derivatives are provided as nonlinear table data as a function of Mach and angle of attack in Appendix C.

TABLE 4. LATERAL-DIRECTIONAL STABILITY DERIVATIVES

Quantity	Definition	Units
Y_v	$\frac{\rho SU}{2m} C_{y_\beta}$	$\frac{1}{sec}$
Y_δ	$\frac{\rho SU^2}{2m} C_{y_\delta}$	$\frac{ft}{sec^2}$
Y_δ^*	$\frac{\rho SU}{2m} C_{y_\delta}$	$\frac{1}{sec}$
N_β	$\frac{\rho SU^2 b}{2I_{zz}} C_{n_\beta}$	$\frac{1}{sec^2}$
N_r	$\frac{\rho SUb^2}{4I_{zz}} C_{n_r}$	$\frac{1}{sec}$
N_δ	$\frac{\rho SU^2 b}{2I_{zz}} C_{n_\delta}$	$\frac{1}{sec^2}$
N_i'	$\frac{N_i + (I_{xz}/I_{zz})L_i}{1-(I_{xz}^2 / I_{xx}I_{zz})}$	
L_β	$\frac{\rho SUb^2}{2I_{xx}} C_{l_\beta}$	$\frac{1}{sec^2}$
L_r	$\frac{\rho SUb^2}{4I_{xx}} C_{l_r}$	$\frac{1}{sec}$
L_δ	$\frac{\rho SU^2 b}{2I_{xx}} C_{l_\delta}$	$\frac{1}{sec^2}$
L_i'	$\frac{L_i + (I_{xz}/I_{xx})N_i}{1-(I_{xz}^2 / I_{xx}I_{zz})}$	

3.0 PROGRAM STRUCTURE

The computer program F18LDTF.EXE is a menu driven program written in Visual Basic Version 2.0 and runs in the Microsoft Windows™ Environment. The program in broken into two main sections, F18LDTF.BAS and F18LDTF.FRM shown in Figure 2. The following bold face sections describe each main section as well as code and subroutines corresponding to each menu option in alphabetical order. A program listing is in Appendix A. Modeled aircraft specifications and the permissible flight envelope are in Appendix B. The plots for the nonlinear data are shown in Appendix C. In addition to the program and data table, an input file with trim Mach, altitude and angle-of-attack is required to run the program. A sample input file is in Appendix D. Note that it includes a case outside of the permissible flight envelope to test for potential input errors. The output file lists the coefficients of the transfer functions for roll rate, roll angle, sideslip, yaw rate and lateral acceleration to lateral stick and pedal inputs for each flight condition evaluated. A sample output file corresponding to the input file of Appendix D is in Appendix E.

calc_rho - Subroutine that calculates the air density as a function of altitude. The equations are based on standard atmospheric relationships.

Files - Menu caption "Files". This subroutine activates the sub-menu options open_tig_Click, output_file_Click and flight_cond_Click. The intent of this option is to allow the user to use and define different input and output data as appropriate.

flight_cond_Click - Menu caption "Open Flight Conditions". Opens a user defined input file. Operates the same as a Windows™ file open command. The input file format is that the first line contains the run title. The following lines lists trim Mach, altitude in feet, and angle-of-attack in radians separated by commas for each flight condition. There is no limit to the number of flight conditions to be listed.

Form_Load - Loads initial data and sets default values at the initial execution of the program. Also sets the error output file for the Dynamic Link Library (DLL) VBREAD to "c:\f18ldtf\error.out".

F18LDTF.BAS - Declares the global variables and arrays, constant values and initializes the DLL TOPEN and TLOOK. TOPEN and TLOOK were modified from Reference 7 to provide a look-up routine for the nonlinear table data.

F18LDTF.FRM - Loads initial data and sets default values at the initial execution of the program. This is the code which also acts as the driver to execute the various menu driven subroutines to read the data tables, input files, calculate the transfer functions and write the transfer functions to an output file. Each menu option is activated by placing the mouse pointer over the menu option and clicking the left mouse button. Figure 3 shows the initial display when the program is activated.

Exit_Click - Menu caption "Exit". Exit program.

mach_to_vel - Subroutine that calculates velocity in ft/sec as a function of Mach and altitude. The equations are based on standard atmospheric relationships.

open_tig_Click - Menu caption "Open Tigs File". This option operates the same as a Windows™ file open command with the default nonlinear data table "c:\f18ldtf\f18ld.dat". The data table is to be used later in the Dynamic Link Library (DLL) VBREAD.

output_file_Click - Menu caption "Output File Name". This option operates the same as a Windows™ file open command with the default output file name "c:\f18ldtf\f18tf.out". The user may change the name as appropriate.

print_tf*x* - Subroutine that prints the Laplace transfer function in descending order of Laplace operator (s) to the output file. The *x* represents the order of the transfer function.

Figure 2. F18LDTF Structure

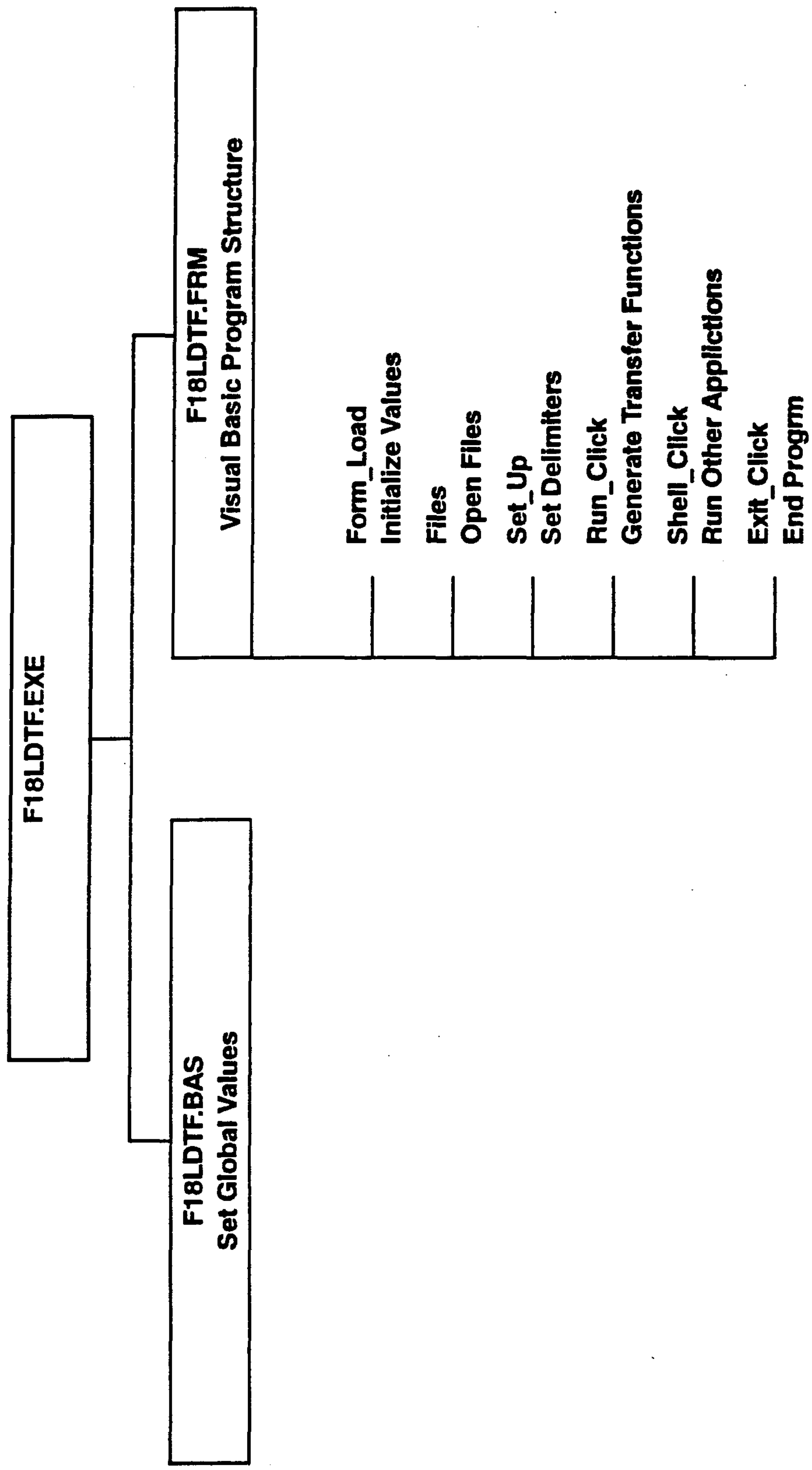
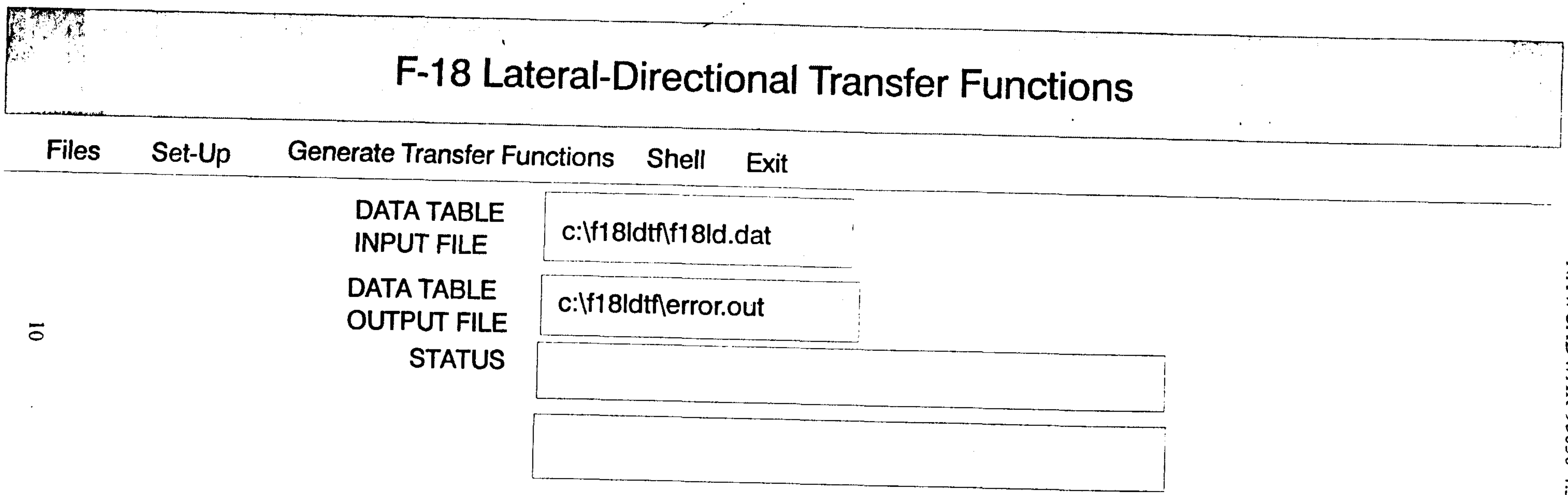


Figure 3. F18LDTF Initial Screen



run_Click - Menu caption "Generate Transfer Functions". This code does the actual computation of the transfer functions for each flight condition in the input file and writes the results to the output file named in output_file_Click. The default output file name is "c:\f18ldtf\f18tf.out".

set_comma_Click - Menu caption "Comma Delimiters". This subroutine sets the delimiters of the coefficients for the transfer functions in the output file to a comma between values.

set_space_Click - Menu caption "Space Delimiters". This subroutine sets the delimiters of the coefficients for the transfer functions in the output file to a single space between values. This is the default setting.

set_tab_Click - Menu caption "Tab Delimiters". This subroutine sets the delimiters of the coefficients for the transfer functions in the output file to tab positions 0, 20, 40, 60, and 80 as appropriate to the order of the transfer function.

Set_Up - Menu caption "Set-up". This subroutine activates the sub-menu options set_space, set_comma, and set_tab. The program defaults to a space delimiter. This option allows the user to customize the output file by defining the delimiters to be used in printing out the transfer functions.

shell_Click - Menu caption "Shell". This subroutine allows the user to exit the program to run other executable files and then return to the program.

speed_cat - Subroutine that determines the speed category (VL, L, M, and H) in which to test MIL-F-8785C Requirement 3.3.4.1. Subroutine inputs are Mach, altitude and velocity. The subroutine calls vmin and vmax to determine the speed limits for the given altitude as defined in the flight envelope in reference 6. These limits are then used to determine the speed category of the trim velocity.

stick_gain - Subroutine that calculates the linearized gains between the lateral stick force input and the aileron and stabilator deflections. The gains are based on the values from References 3 and 4.

test_drdamp - Subroutine that tests nonlinear table value for Dutch roll damping (ς_d). If $\varsigma_d < 0.4$ then the code sets $\varsigma_d = 0.4$.

test_envelope - Subroutine that tests whether or not the trim conditions are within the permissible flight envelope of the F-18 modeled in this program. The program tests against the envelope as a function of Mach and altitude. It does not test for stall angle-of-attack.

test_freq - Subroutine that tests nonlinear table value for Dutch roll frequency (ω_d). If $\omega_d < 1.0$ rad/sec then the code sets $\omega_d = 1.0$ rad/sec.

test_phi - Subroutine that tests the roll sensitivity and time to roll requirements. If the time to roll requirement is not met then the numerator gain is increased by 10% until the requirements is met. If the roll sensitivity is too high the numerator gain is set to the maximum requirement value.

test_stick - Subroutine that determines the maximum stick force input to as a function of p_{SS}. The stick force is the same as the design curve shown in Figure 1.

vmax - Subroutine that computes the maximum speed as a function of altitude for the permissible flight envelope for the F-18 at a gross weight of 42097 lbs.

vmin - Subroutine that computes the minimum speed as a function of altitude for the permissible flight envelope for the F-18 at a gross weight of 42097 lbs.

4.0 PROGRAM OPERATION

4.1 SYSTEM REQUIREMENTS

The program was designed in the Microsoft® Visual Basic ™ Version 2.0 programming system for Windows™ Ver. 2.0 higher. The program runs from mouse inputs and requires 1.2 MB disk space to load the distribution disk onto the host system. The distribution disk contains the executable code, the program source code, the custom controls (denoted with the extension "VBX") required to run the program, the dynamic-link library (DLL) executable and source codes for VBREAD that executes the table look-up routine for the F-18 data tables used in the program and a sample input file (F18TRIM.INP) and output file (F18TF.OUT).

4.2 INSTALLATION

The Setup program will install the program and source code in a directory called "f18ldtf". For reference purpose, it will be assumed that the floppy drive designation is A, the hard drive designation is C and the user is in the Windows™ environment. To install the program insert the floppy disk into the A drive. In the Program Manager, choose Run from the File Menu, and then type:

A:setup <RETURN>

The Setup program will create and copy the following files into the C:\F18LDTF\ directory:

F18LDTF.BAS
F18LD.DAT
F18LDTF.EXE
F18LDTF.FRM
F18LDTF.MAK
F18TF.OUT
F18TRIM.INP
ERROR.OUT
VBREAD.DLL
VBREAD.FOR
VBREAD.DEF

Into C:\WINDOWS\SYSTEM\ directory the following custom control files will be copied:

ANIBUTON.VBX
CMDIALOG.VBX
GAUGE.VBX
GRAPH.VBX
GRID.VBX
KEYSTAT.VBX
MSCOMM.VBX
MSMASKED.VBX
OLECLIEN.VBX
PICCLIP.VBX
SPIN.VBX
THREED.VBX
VBRUN200.DLL

4.3 PROGRAM EXECUTION

The following instructions will describe how to invoke "F18LDTF" and run a sample session. To invoke the executable program go to the Program Manager in the Windows environment. Choose Run from the File Menu and type:

C:\F18LDTF\F18LDTF <RETURN>

Figure 3 shows what will appear on the screen at program execution. To run the program use the mouse to click on the various menu options. The following instructions will describe the recommended order in which to exercise the various menu options.

1. Move the mouse to "Files" and select the option "Open Tigs File". The default file "c:\f18ldtf\f18ld.dat" will appear. Click the "OK" button. When the data file is read in, the message "DLL LIB TOPEN COMPLETE" will appear on the screen in the "STATUS" text box .

2. Move the mouse to "Files" and the option "Open Flight Conditions" and click on. This option operates the same as a Windows™ file open command. The sample input file is in "c:\f18ldtf\f18trim.inp". The user may create their own input file for transfer function file generation. Click the "OK" button when the appropriate input file is highlighted. In the "STATUS" text box a message will appear stating input flight condition file is open.

3. Move the mouse to "Set Up". The default delimiter between the coefficients of the transfer function is a space. If the user requires a different delimiter the user may select the option for a comma, space or tab delimiter. A message will appear in the "STATUS" text box stating which delimiter was selected. If the space is a satisfactory delimiter then the user may skip this option.

4. Select the "Generate Transfer Functions" option. While the program is reading in the flight conditions and generating the transfer functions the message "Generating Transfer Functions" will appear in the "STATUS" text box. In the box below the "STATUS" text box the message "Case Number *x*" will appear for each flight condition case. Upon completion, the message "Generation of Transfer Functions Complete" and "Transfer Functions Saved to File F18TF.OUT" will appear in the "STATUS" text boxes.

5. Select "Exit" to leave the program.

6. If the user desires to run additional executable, batch or command files, the "Shell" option may be invoked. This is useful if the user would like to view or edit the output file prior to exiting the program.

5.0 CONCLUSIONS

This report documents the development of a computer program that generates Level 1 lateral-directional transfer functions for a Class IV airplane that meet requirements of MIL-F-8785C given a trim Mach, altitude and angle-of-attack flight conditions. The data used to generate the transfer functions were representative of an F-18 and will support the effort being done at C. S. Draper Laboratory, Inc. to develop a hybrid, learning augmented, lateral-directional flight control system. Also presented in this report is the structure of the computer code, instructions for running the program, sample input and sample output.

REFERENCES

1. Anonymous, "Military Specification, Flying Qualities of Piloted Airplanes", MIL-F-8785C, November 1980.

2. McRuer, D., Ashkenas, I., and Graham, D. "Aircraft Dynamics and Automatic Control", Princeton, New Jersey, Princeton University Press, 1973.

3. McDonnell Aircraft Company, "F/A-18A Flight Control System Design Report Volume II Flight Control Analysis - Inner Loops", Report Number MDC A7813, June 1984.

4. Veda Inc., "Final Report - Generic Fighter Aircraft Faster Simulation Model Report", Veda Report Number 33159-91U/P3551-005, January 1991.

5. Anonymous, "Military Standard, Flying Qualities of Piloted Aircraft", MIL-STD-1797A, January 1990.

6. McDonnell Aircraft Company, "F/A-18E/F Performance and Control Analysis Summary Volume III Flying Qualities and Flight Control Analysis", Report Number MDC 92B0013, January 1992.

7. Caddy, M. J., "TREAD/TLOOK-Multipurpose Computer Routine for Interpolation and Extrapolation of Tabular Data", NADC Report No. 76366-30, January 1977.

APPENDIX A

F18LDTF SOURCE CODE

Filename: B:\F18LDTF.BAS Printed on: 03/30/94 04:22 PM

```
Option Explicit
Declare Sub TOPEN Lib "VBREAD.DLL" (ByVal INFILE As String, ByVal OUTFILE As String)
Declare Sub tlook Lib "VBREAD.DLL" (Table As Integer, X As Single, Y As Single, Z As
Single, FXYZ As Single)
'
' Declare Global Variables
'
Global mach As Single, alt As Single, alpha As Single
Global taur As Single, pssmax As Single, drfreq As Single, drdamp As Single
Global cydr As Single, cldr As Single, cndr As Single, cnr As Single, clr As Single
Global cyda As Single, clda As Single, cnda As Single, cnb As Single, clb As Single
Global cyb As Single, cyds As Single, clds As Single, cnds As Single
Global fstick, fpedal, Lprime_fstick, tab_flag, phit
Global Flt_con_file$, sep$, speedcat$, ncase, test_case_flag
'
'  The following are the arrays that define the transfer fuctions used to define
'  the Level 1 Flying Qualities.  Those values corresponding to array_name(x) are
'  the values of the numerator of the transfer function is descending order of s and
'  the values corresponding to denominator(x) are the values of the denominator of
'  the transfer functions.
'
 Global p_to_fstick(4), phi_to_fstick(3), beta_to_frud(2), r_to_frud(5)
 Global p_to_frud(5), phi_to_frud(5), beta_to_fstick(2), r_to_fstick(5)
 Global aycg_to_frud(5), aycg_to_fstick(5), denominator(5), f(5)
'
' Declare Global Constants
'
Global Const tab_num_taur = 1
Global Const tab_num_freq = 2
Global Const tab_num_damp = 3
Global Const tab_num_pssmax = 4
Global Const tab_num_cydr = 5
Global Const tab_num_cldr = 6
Global Const tab_num_cndr = 7
Global Const tab_num_cnr = 8
Global Const tab_num_clr = 9
Global Const tab_num_cyda = 10
Global Const tab_num_clda = 11
Global Const tab_num_cnda = 12
Global Const tab_num_cyb = 13
Global Const tab_num_cnb = 14
Global Const tab_num_clb = 15
Global Const tab_num_cyds = 16
Global Const tab_num_clds = 17
Global Const tab_num_cnds = 18

Global Const Z = 1
Global Const num_files = 3
Global Const dot$ = "."
Global Const blank$ = " "
Global Const comma$ = ","
Global Const Ixx = 124000  'slug-sq.ft
Global Const Izz = 143000  'slug-sq.ft
Global Const Ixz = -2971  'slug-sq.ft
Global Const span = 37.44   'ft
Global Const S = 400        ' sq. ft
Global Const mass = 1308.4
Global Const force_to_rud_gain = -.00262 'rad per lb right pedal => left rudder &
vice versa
Global Const rad_to_deg = 57.29578
Global Const g = 32.174'ft/sec^2
Global Const t30 = 1.1 'sec
Global Const t50 = 1.1 'sec
Global Const t90 = 1.3 'sec
Global Const lb_per_in = 3.66667
Global Const stk_to_stab = .04
Global Const stk_to_ail1 = .075
Global Const stk_to_ail2 = .1125
Global Const atm_con = .00000689 'atmospheric constant for computing density
```

```
Sub calc_rho (alt, rho)
'
'         CALCULATE DENSITY
'

          T88 = 288.15
          THERAT = 1# - alt * atm_con
          If (alt >= 36089#) Then THERAT = .75134679
          DELRAT = (T88 / (T88 - .00198 * alt)) ^ (-5.256)
          rho = (DELRAT / THERAT) * .002377
'

End Sub

Sub Exit_Click ()

     End

End Sub

Sub flight_cond_Click ()

  cmdialog1.Filename = "c:\f18ldtf\f18trim.inp"  'Default name
  cmdialog1.Action = 1
  Flt_con_file$ = cmdialog1.Filename
  Open Flt_con_file$ For Input As #3
  Text3.Text = "Flt. Cond. File " + cmdialog1.Filename + " Open"

End Sub

Sub Form_Load ()

  text2.Text = "c:\f18ldtf\error.out"

  OUTFILE = text2.Text

  '
  'define initial constants
  '
   denominator(1) = 1
   denominator(5) = 0
   tab_flag = 0
   sep$ = blank$

   speedcat$ = "VL"
   Mach_min_val = .19
   Mach_max_val = 1.1
   phit = 1
   fstick = 13' max lateral stick input (lbs)

End Sub

Sub mach_to_vel (mach, alt, vel)

'     CALCULATE VELOCITY (FT/SEC) FROM MACH AND ALT
'
          THERAT = 1# - alt * atm_con

'
'         NOTE CONSTANT TEMP AFTER 36089 FT (US STD ATM)
'
          If (alt >= 36089#) Then THERAT = .75134679
          DIVCON = Sqr(1.4 * 32.2 * 53.35 * THERAT * 518.6)
          vel = DIVCON * mach

End Sub

Sub open_tig_Click ()

   Dim INFILE As String * 80
   Dim OUTFILE As String * 80


  cmdialog1.Filename = "c:\f18ldtf\f18ld.dat" 'Default name
  cmdialog1.Action = 1


  INFILE = cmdialog1.Filename
  OUTFILE = text2.Text

  Call TOPEN(INFILE, OUTFILE)
  Text3.Text = "DLL LIB TOPEN COMPLETE"

End Sub

Sub output_file_Click ()


  cmdialog3.Filename = "c:\f18ldtf\F18TF.OUT" 'Default name
  cmdialog3.Action = 1

   Open cmdialog3.Filename For Output As #2

End Sub

Sub print_tf2 (tf())

    For i = 1 To 2
     f(i) = Format(tf(i), "#######.000000")
    Next i

   If tab_flag = 0 Then

     Print #2, f(1); sep$; f(2)

    ElseIf tab_flag = 1 Then

     Print #2, f(1); Tab(20); f(2)

   End If


End Sub

 Sub print_tf3 (tf3())

    For i = 1 To 3
     f(i) = Format(tf3(i), "#######.000000")
    Next i

   If tab_flag = 0 Then
```

```
      Print #2, f(1); sep$; f(2); sep$; f(3)

     ElseIf tab_flag = 1 Then

      Print #2, f(1); Tab(20); f(2); Tab(40); f(3)

    End If

End Sub

Sub print_tf4 (tf4())

     For i = 1 To 4
      f(i) = Format(tf4(i), "#######.000000")
     Next i


    If tab_flag = 0 Then

      Print #2, f(1); sep$; f(2); sep$; f(3); sep$; f(4)

    ElseIf tab_flag = 1 Then

      Print #2, f(1); Tab(20); f(2); Tab(40); f(3); Tab(60); f(4)

    End If

End Sub

Sub print_tf5 (tf5())

     For i = 1 To 5
      f(i) = Format(tf5(i), "#######.000000")
     Next i

    If tab_flag = 0 Then

      Print #2, f(1); sep$; f(2); sep$; f(3); sep$; f(4); sep$; f(5)

     ElseIf tab_flag = 1 Then

      Print #2, f(1); Tab(20); f(2); Tab(40); f(3); Tab(60); f(4); Tab(80); f(5)

    End If

End Sub

Sub run_Click ()
   '
   '   Level 1  Flying Qualities are generally defined by the roots
   '   of the transfer function.  For lateral-directional Flying Qualities
   '   those valus are described by the roll mode, the spriral mode, and
   '   the dutch roll frequency and damping.  This program will look-up
   '   values for an F-18 for these modal values and test them against the
   '   MIL-Spec-8785C.  In those instances that the values do not meet the
   '   Level 1 criteria the modal value will be reset to the minimum allowable
   '   spec value.  This was done so that the variation in modal characterists
   '   do to the flight conditions would be representative of the F-18.
   '
   '   Simplifying approximations were made in generating the transfer
   '   functions to yeild Level 1 time histories that should by within the F-18's
   '   capabiliies to achieve.
   '
   '   Note that these transfer functions are applicable to trimmed flight condtions
   '   with flight path angle = 0 so that the Mach, alt and angle-of-attack values
   '   correspond to those trimmed values.
   '
   '    One such simplifying approximation is that the spiral mode = 0 throughout
   '    the flight envelope.
   '
   '    The roll characteristics are based on the approximation that
   '    pssmax = L'fas*taur*Fstick_full.
   '    Then p/fstick=L'fas/(s+1/taur) and Phi/fstick=L'fas/(s*(s+1/taur))
   '    This will be the low-order numerator approximation for
   '    the p and Phi transfer functions with the additional assumption
   '    that the p and phi numerator freq. & damping = dutch roll freq & damping.
   '
   '    The dutch roll characteristics are based on the 3 Degree-Of-Freedom
   '    Dutch Roll approximation to provide the numerator characteristics
   '    for the beta and r transfer functions to both the lateral stick
   '    and rudder input.  This approximation was also used to generate
   '    the roll response to pedal inputs.
   '


  Input #3, title$
  Text3.Text = "Generating Transfer Functions"
  Print #2, title$
  Print #2, blank$

  ncase = 0

  Ixz_div_Ix = Ixz / Ixx
  Ixz_div_Iz = Ixz / Izz
  one_minus_Ixz2_div_IxIz = 1 - Ixz_div_Ix * Ixz_div_Iz

  '  Read in mach, altitude and angle-of-attack

Do While Not EOF(3)
   Input #3, mach, alt, alpha

   ncase = ncase + 1
   fmach = Format(mach, "##.000")
   falt = Format(alt, "######.0")
   falpha = Format(alpha, "##.000")
   fncase = Format(ncase, "#####")

   Text4.Text = "Case Number " + fncase

 Print #2, "Case Number "; fncase
 Print #2, "mach = "; fmach; "  alt = "; falt; "  alpha(rad) = "; falpha

 '    Test that trim condition is within the
 '    flight envelope for the F-18 otherwise go to next
 '    flight condition

 Call test_envelope(alt, mach, env_flag)

  If env_flag = 1 Then
```

```
   Print #2, "Trim flight conditions outside of permissible flight envelope"
   GoTo 10

 End If

Call mach_to_vel(mach, alt, vel)
Uo = vel * Cos(alpha)

Call calc_rho(alt, rho)
q = .5 * rho * Uo * Uo
'
'   Determing the speed category to
'   test for time to bank
'
Call speed_cat(mach, alt, vel, speedcat$)

'
'    Do table look-ups
'

Call tlook(tab_num_taur, mach, alt, s, taur)
Call tlook(tab_num_freq, mach, alt, s, drfreq)
Call tlook(tab_num_damp, mach, alt, s, drdamp)
Call tlook(tab_num_pssmax, mach, alt, s, pssmax)
Call tlook(tab_num_cydr, mach, alpha, s, cydr)
Call tlook(tab_num_cldr, mach, alpha, s, cldr)
Call tlook(tab_num_cndr, mach, alpha, s, cndr)
Call tlook(tab_num_cnr, mach, alpha, s, cnr)
Call tlook(tab_num_clr, mach, alpha, s, clr)
Call tlook(tab_num_cyda, mach, alpha, s, cyda)
Call tlook(tab_num_clda, mach, alpha, s, clda)
Call tlook(tab_num_cnda, mach, alpha, s, cnda)
Call tlook(tab_num_cyds, mach, alpha, s, cyds)
Call tlook(tab_num_clds, mach, alpha, s, clds)
Call tlook(tab_num_cnds, mach, alpha, s, cnds)
Call tlook(tab_num_cyb, mach, alpha, s, cyb)
Call tlook(tab_num_cnb, 1, alpha, s, cnb)
Call tlook(tab_num_clb, mach, alpha, s, clb)


Call test_taur(taur)
Call test_freq(drfreq)
Call test_drdamp(drdamp)
'
'  Determine the coefficients for the denominator of
'  the transfer functions in descending order of s.
'  The denomiatior is an expanded representation of
'  The 3 DOF  Dutch Roll Approximation where in the
'  s domain  the  denominator is as follows:
'  s*(s+taur)*(s^2 + 2*drdamp*drfreq*s + drfreq^2)
'  denominator(1)=1 and denominator(5) =0  already set in
'  Form Load

two_z_w = 2 * drdamp * drfreq
wn2 = drfreq * drfreq
denominator(2) = two_z_w + taur
denominator(3) = wn2 + taur * two_z_w
denominator(4) = taur * wn2
 '
 ' Format denominator values
 '

 Print #2, blank$
 Print #2, " Denominator to Lateral-Directional Transfer Functions."
 Print #2, " Coefficients are in descending order of s."
 Print #2, blank$

 Call print_tf5(denominator())

' *****************************************************************
'                    Lateral Requirements
' *****************************************************************
 '

'
Call test_stick(fstick, pssmax)

Call stick_gain(fstick, force_to_ail_gain, force_to_stab_gain)

Lprime_fstick = pssmax / (taur * fstick)

Call test_phi(Lprime_fstick, taur, pssmax, speedcat$)

p_to_fstick(1) = Lprime_fstick
p_to_fstick(2) = Lprime_fstick * two_z_w
p_to_fstick(3) = Lprime_fstick * wn2
p_to_fstick(4) = 0

phi_to_fstick(1) = Lprime_fstick
phi_to_fstick(2) = Lprime_fstick * two_z_w
phi_to_fstick(3) = Lprime_fstick * wn2

Print #2, blank$
Print #2, " p to lateral stick force transfer function numerator"

 Call print_tf4(p_to_fstick())

Print #2, blank$
Print #2, " phi to lateral stick force transfer function numerator"

 Call print_tf3(phi_to_fstick())

' *****************************************************************
'                    Directional Requirements
' *****************************************************************
'
'  The Dutch Roll requirement will be met with a three degree of freedom
'  dutch roll approximation for sideslip to rudder input
'
'  The denominator will be represented by the dutch roll frequency and
'  damping.
'
'  The numerator will be represented by a first order transfer function.
'  In "Aircraft Dynamics and Automatic Control" by McRuer, Ashkenas, and Graham
'  the numerator is defined in as (Ydrstar)*[s-Nr'-(Ndr'/Ydrstar)].
'  Where
'     Ydrstar = Ydr/Uo
'     Nr'     = Nr + (Ixz/Iz)Lr/(1-(Ixz^2/(IxxIzz)))
'     Ndr'    = Ndr + (Ixz/Iz)Ldr/(1-(Ixz^2/(IxxIzz)))
'
'  Pedal Gain is based on the F/A - 18 like gearing used in the generic
'  fighter model hosted in the FASTER lab here at NAWC-AD WAR
'
'
```

Filename: B:\F18LDTF.FRM Printed on: 03/31/94 10:03 AM

```
'  Calculate dimensional derivatives
'

Ydrstar = cydr * rho * S * Uo / (2 * mass)
Ydastar = cyda * rho * S * Uo / (2 * mass)
Ydsstar = cyds * rho * S * Uo / (2 * mass)
Yv = cyb * rho * S * Uo / (2 * mass)
Nr = cnr * q * S * span * span / (2 * Uo * Izz)
Lr = clr * q * S * span * span / (2 * Uo * Ixx)
Nb = cnb * q * S * span / Izz
Lb = clb * q * S * span / Ixx
Ndr = cndr * q * S * span / Izz
Ldr = cldr * q * S * span / Ixx
Nda = cnda * q * S * span / Izz
Lda = clda * q * S * span / Ixx
Nds = cnds * q * S * span / Izz
Lds = clds * q * S * span / Ixx

Nrprime = (Nr + (Ixz_div_Iz) * Lr) / one_minus_Ixz2_div_IxIz
Ndrprime = (Ndr + (Ixz_div_Iz) * Ldr) / one_minus_Ixz2_div_IxIz
Ldrprime = (Ldr + (Ixz_div_Ix) * Ndr) / one_minus_Ixz2_div_IxIz


Nbprime = (Nb + (Ixz_div_Iz) * Lb) / one_minus_Ixz2_div_IxIz
Lbprime = (Lb + (Ixz_div_Ix) * Nb) / one_minus_Ixz2_div_IxIz
Ndaprime = (Nda + (Ixz_div_Iz) * Lda) / one_minus_Ixz2_div_IxIz
Ndsprime = (Nds + (Ixz_div_Iz) * Lds) / one_minus_Ixz2_div_IxIz

'
'  Computer transfer function numerators
'

   '  Test to prevent division by 0

   If Ldrprime = 0 Then

    phi_to_frud(1) = 0
    phi_to_frud(2) = 0
    phi_to_frud(3) = Yv * Nrprime - Ydrstar * Lbprime * Nrprime / .000001' Set
Ldrprime to Small Number

   Else

    phi_to_frud(1) = force_to_rud_gain * rad_to_deg * Ldrprime
    phi_to_frud(2) = force_to_rud_gain * rad_to_deg * Ldrprime * (-Yv - Nrprime +
Ydrstar * Lbprime / Ldrprime)
    phi_to_frud(3) = force_to_rud_gain * rad_to_deg * Ldrprime * (Nbprime * (1 -
Lbprime * Ndrprime / (Ldrprime * Nbprime)) + Yv * Nrprime - Ydrstar * Lbprime *
Nrprime / Ldrprime)

   End If

  p_to_frud(1) = phi_to_frud(1)
  p_to_frud(2) = phi_to_frud(2)
  p_to_frud(3) = phi_to_frud(3)
  p_to_frud(4) = 0

  If Ydrstar = 0 Then
    beta_to_frud(1) = 0
    beta_to_frud(2) = 0
  Else

    beta_to_frud(1) = force_to_rud_gain * rad_to_deg * Ydrstar
    beta_to_frud(2) = force_to_rud_gain * rad_to_deg * Ydrstar * (-Nrprime -
(Ndrprime / Ydrstar))
  End If

  beta_to_fstick(1) = 0  'to assure 0 sideslip in rolls by effectively subtracting
any beta
  beta_to_fstick(2) = 0  ' generated and thus setting the response to zero

   r_to_frud(1) = force_to_rud_gain * rad_to_deg * Ndrprime
   r_to_frud(2) = force_to_rud_gain * rad_to_deg * Ndrprime * (-Yv - (Ydrstar /
Ndrprime) * Nbprime)

   r_to_stab1 = force_to_ail_gain * Ndsprime
   r_to_ail1 = force_to_stab_gain * Ndaprime
   r_to_stab2 = force_to_stab_gain * Ndsprime * (-Yv - (Ydsstar / Ndsprime) *
Nbprime)
   r_to_ail2 = force_to_ail_gain * Ndaprime * (-Yv - (Ydastar / Ndaprime) * Nbprime)

   r_to_fstick(1) = (r_to_stab1 + r_to_ail1) * rad_to_deg
   r_to_fstick(2) = (r_to_stab2 + r_to_ail2) * rad_to_deg
'
'  An auxilary relationship that is provided for simultaneous time history matching
'  is the acceleration in the y direction due to rudder & stick inputs.
'  the equation for aycg = Uo*betadot -g*phi +Uo*r

  aycg_to_frud(1) = (Uo * beta_to_frud(1) - g * phi_to_frud(1)) / rad_to_deg
  aycg_to_frud(2) = (Uo * beta_to_frud(2) - g * phi_to_frud(2) + Uo * r_to_frud(1))
/ rad_to_deg
  aycg_to_frud(3) = (-g * phi_to_frud(3) + Uo * r_to_frud(2)) / rad_to_deg

  aycg_to_fstick(1) = (Uo * beta_to_fstick(1) - g * phi_to_fstick(1)) / rad_to_deg
  aycg_to_fstick(2) = (Uo * beta_to_fstick(2) - g * phi_to_fstick(2) + Uo *
r_to_fstick(1)) / rad_to_deg
  aycg_to_fstick(3) = (-g * phi_to_fstick(3) + Uo * r_to_fstick(2)) / rad_to_deg

  Print #2, blank$
  Print #2, " beta to lateral stick force transfer function numerator"

  Call print_tf2(beta_to_fstick())

  Print #2, blank$
  Print #2, " r to lateral stick force transfer function numerator"

  Call print_tf2(r_to_fstick())

  Print #2, blank$
  Print #2, " aycg to lateral stick force transfer function numerator"

  Call print_tf3(aycg_to_fstick())

  Print #2, blank$
  Print #2, " p to pedal force transfer function numerator"

  Call print_tf4(p_to_frud())

  Print #2, blank$
  Print #2, " phi to pedal force transfer function numerator"
```

```
    Call print_tf3(phi_to_frud())

    Print #2, blank$
    Print #2, " beta to pedal force transfer function numerator"

    Call print_tf2(beta_to_frud())

    Print #2, blank$
    Print #2, " r to pedal force transfer function numerator"

    Call print_tf2(r_to_frud())

    Print #2, blank$
    Print #2, " aycg to pedal force transfer function numerator"

    Call print_tf3(aycg_to_frud())

10  Print #2, blank$

  Loop

    Close #2
    Close #3

  Text3.Text = "Generation of Transfer Functions Complete"
  Text4.Text = "Transfer Functions Saved to File " + cmdialog3.Filename

End Sub


Sub save_mod_Click ()

End Sub

Sub set_comma_Click ()

    sep$ = comma$
    tab_flag = 0
    Text3.Text = "Delimiters Set To Commas"

End Sub

Sub set_space_Click ()

    sep$ = blank$
    tab_flag = 0
    Text3.Text = "Delimiters Set To Spaces"

End Sub

Sub set_tab_Click ()

     tab_flag = 1
     Text3.Text = "Delimiters Set To Tabs"

End Sub

Sub shell_Click ()

' ... set dialog default extension filename ...

   cmdialog2.DialogTitle = "Executable Files"
   cmdialog2.Filter = "Exe Files  (*.exe)|*.exe|Com Files  (*.com)|*.com|Batch Files
(*.bat)|*.bat"
   cmdialog2.Filename = "*.exe"
   cmdialog2.Action = 1  'opens file


' ... open the selected file ...

         x = Shell(cmdialog2.Filename, 3)


End Sub

 Sub speed_cat (mach, alt, vel, speedcat$)

    Call vmin(alt, Mach_min_val)
    Call vmax(alt, Mach_max_val)
    Call mach_to_vel(Mach_min_val, alt, vmin_val)
    Call mach_to_vel(Mach_max_val, alt, vmax_val)

    vmin20 = vmin_val + 33.77778
    v0min = 1.4 * vmin_val
    v7max = .7 * vmax_val


    If vel >= vmin_val And vel < vmin20 Then

         speedcat$ = "VL"

      ElseIf vel >= vmin20 And vel < v0min Then

         speedcat$ = "L"

     ElseIf vel >= vel And vel < v7max Then

         speedcat$ = "M"

    ElseIf vel >= v7max And vel <= vmax_val Then

         speedcat$ = "H"

    End If

End Sub

Sub stick_gain (fstick, gaina, gains)

'   This gain is computed from data used in NAWC-AC FASTER
'   LAB.  This is needed to compute the stick force gain necessary
'   to generate the transfer functions.
'
'   From MDC A7813 VOL. I REV B page 9-14
'   the stick force to stick deflection gain  is 3.6667 lb/in

'   Compute stick deflection from the force

    stick_in = fstick / lb_per_in
    sign_stick = Sgn(fstick)
```

```
    gains = sign_stick * stk_to_stab / lb_per_in ' units = (rad/in)*(in/lb)
                                                 'stk_to_stab =.04 rad/in

      If Abs(stick_in) <= 1 Then

        gaina = sign_stick * stk_to_ail1 / lb_per_in' units = (rad/in)*(in/lb)
                                                   'stk_to_ail1 =.075 rad/in
      Else

        gaina = sign_stick * stk_to_ail2 / lb_per_in  ' units = (rad/in)*(in/lb)
                                                   'stk_to_ail2=.1125 rad/in
      End If

End Sub

Sub test_drdamp (damp)

    If damp < .4 Then
        damp = .4
    End If

End Sub

 Sub test_envelope (alt, mach, env_flag)

'    Tests that trim flight conditions are
'    within the permissable flight envelope.
'    If not will skip this case and go
'    to next trim case in input file

     Call vmin(alt, mach_min)   ' Determine min Mach for altitude
     Call vmax(alt, mach_max)   ' Determine max Mach for altitude

    If mach < mach_min Or mach > mach_max Then

        env_flag = 1

    Else

       env_flag = 0

    End If


End Sub

Sub test_freq (freq)

     If freq < 1# Then
        freq = 1#
    End If



End Sub

Sub test_phi (lf, tau, pssmax, speedcat$)

       lf_old = lf

       ft30 = Format(t30, "###.00")
       ft50 = Format(t50, "###.00")
       ft90 = Format(t90, "###.00")
       tau_term = 1 - Exp(-1 * tau) 'unit step response in 1 second

100    phie = lf * (1 - Exp(-1 * tau))

    If phie >= 15 Then   ' test for stick sensitivity

        lf = 15 / tau_term
        phie = lf * (1 - Exp(-1 * tau))

     End If

  Select Case speedcat$

     Case "VL", "L"   '  test for 30 deg bank angle change

        phi30 = fstick * lf * (1 - Exp(-t30 * tau))

           If phi30 < 30 Then
            lf = 1.1 * lf
            GoTo 100    'check that lf still meets stick sensitivity req'ts
           End If


    Case "M"  '  test for 90 deg bank angle change

      phi90 = fstick * lf * (1 - Exp(-t90 * tau))

      If phi90 < 90 Then

        lf = 1.1 * lf
        GoTo 100        'check that lf still meets stick sensitivity req'ts

      End If


   Case "H"   '  test for 50 deg bank angle change

      phi50 = fstick * lf * (1 - Exp(-t50 * tau))

      If phi50 < 50 Then
        lf = 1.1 * lf    'check that lf still meets stick sensitivity req'ts
        GoTo 100
      End If


  End Select

End Sub

 Sub test_stick (fstick, pss)

    '  maximum input stick force is a function of pss to
    '  to help in preventing too much roll sensitivity
    '  the curve fits with in  the region specified in
    '  Figure 194 pg 480 MIL-SPEC-8785A



     If pss >= 80 And pss < 200 Then
```

```
        fstick = 9 + .03333 * (pss - 80)

    ElseIf pss >= 18.75 And pss < 80 Then

        fstick = 5 + .06531 * (pss - 18.75)

    ElseIf pss < 18.75 Then

        fstick = 1 + .21333 * pss

    End If


End Sub

Sub test_taur (tau)

     If tau < .3 Then tau = .3
     If tau > 1# Then tau = 1#

End Sub

Sub vmax (alt, Mach_max_val)
'
' this subroutine computes the values for
' the maximum speed for the permissible flight
' envelope for the F-18 for a gross weight of
' 42,097 lbs.  The values computed here will be
' used to determine the values for the time to roll requirements
'
    If alt < 20000 Then

      Mach_max_val = 1.1 + .000027 * alt

    ElseIf alt >= 20000 And alt < 35000 Then

      Mach_max_val = 1.64 + .000024 * (alt - 20000)

    ElseIf alt >= 35000 And alt < 45000 Then

      Mach_max_val = 2#

    ElseIf alt >= 45000 And alt < 50000 Then

      Mach_max_val = 2# - .000068 * (alt - 45000)

    ElseIf alt >= 50000 And alt <= 51000 Then

      Mach_max_val = 1.64 - .00008 * (alt - 50000)

    ElseIf alt >= 51000 And alt < 53000 Then

      Mach_max_val = 1 - .00003 * (alt - 51000)

    ElseIf alt >= 53000 Then

      Mach_max_val = .94

    End If
```

```
End Sub

Sub vmin (alt, Mach_min_val)
'
' this subroutine computes the values for
' the minimum speed for the permissible flight
' envelope for the F-18 for a gross weight of
' 42,097 lbs.  The values computed here will be
' used to determine the values for the time to roll requirements
'
    If alt < 20000 Then

      Mach_min_val = .19 + .0000046 * alt

    ElseIf 20000 >= alt And alt < 30000 Then

      Mach_min_val = .28 + .000006 * (alt - 20000)

    ElseIf alt >= 30000 And alt < 34000 Then

      Mach_min_val = .34 + .000015 * (alt - 30000)

    ElseIf alt >= 34000 And alt < 43000 Then

      Mach_min_val = .4 + .00001556 * (alt - 34000)

    ElseIf alt >= 43000 And alt < 50000 Then

      Mach_min_val = .54 + .00001176 * (alt - 43000)

    ElseIf alt >= 50000 And alt < 53000 Then

       Mach_min_val = .74 + .00004 * (alt - 50000)

    ElseIf alt >= 53000 Then

       Mach_min_val = .86

    End If


End Sub
```

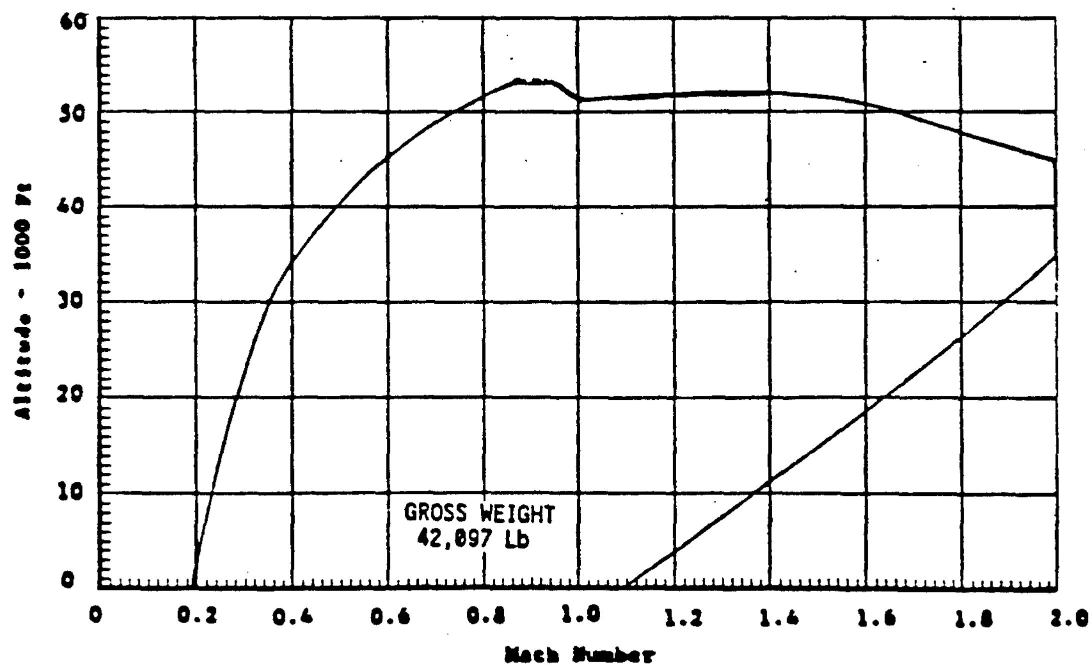
APPENDIX B

MODELED AIRCRAFT SPECIFICATIONS

TABLE B1. BASIC AIRCRAFT PARAMETERS

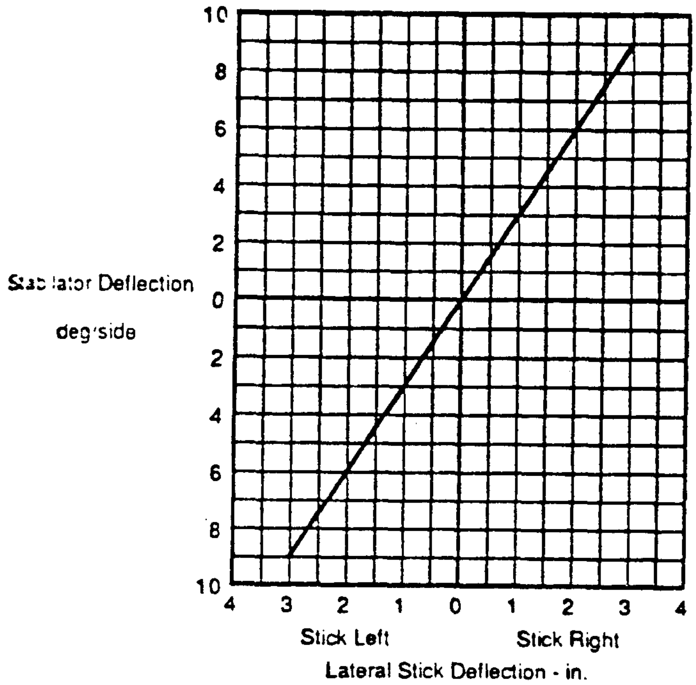
PARAMETER	UNITS	VALUE
Gross Weight	lbs	42097
Mass	slugs	1308.4
I_{xx}	slug-ft^2	12400
I_{zz}	slug-ft^2	14300
I_{xz}	slug-ft^2	-2971
S	ft^2	400
b	ft	37.44

FIGURE B1. PERMISSIBLE FLIGHT ENVELOPE



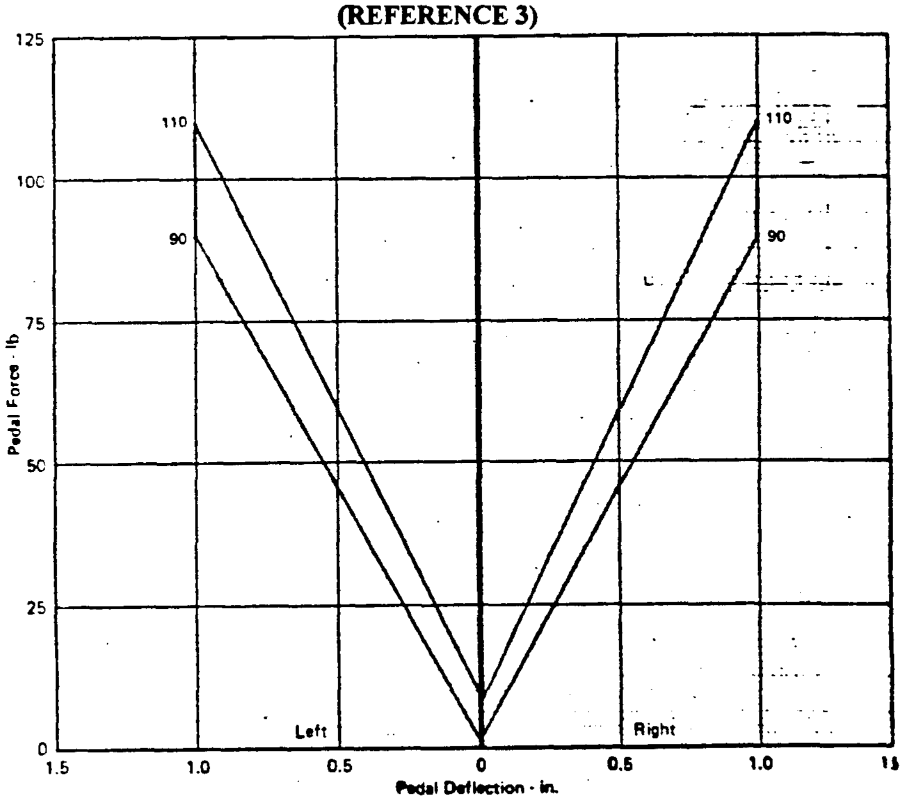
PERMISSIBLE

FIGURE B2. LATERAL STICK FORCE VS. STICK DEFLECTION (REFERENCE 3)



Stabilator Deflection vs Lateral Stick Deflection

FIGURE B3. PEDAL FORCE VS. PEDAL DEFLECTION (REFERENCE 3)



DIRECTIONAL PEDAL FORCE vs PEDAL DEFLECTION

FIGURE B4. DIFFERENTIAL STABILATOR GEARING CURVE (REFERENCE 4)

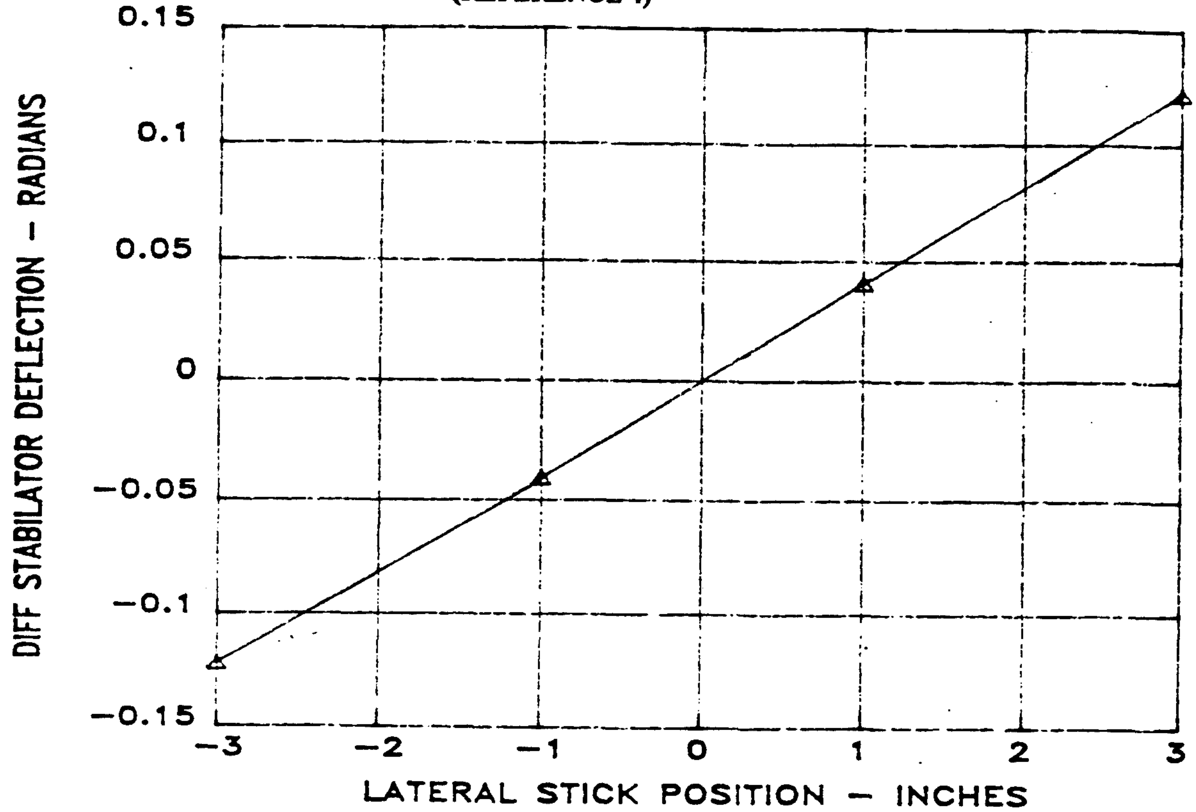


FIGURE B5. AILERON GEARING CURVE (REFERENCE 4)

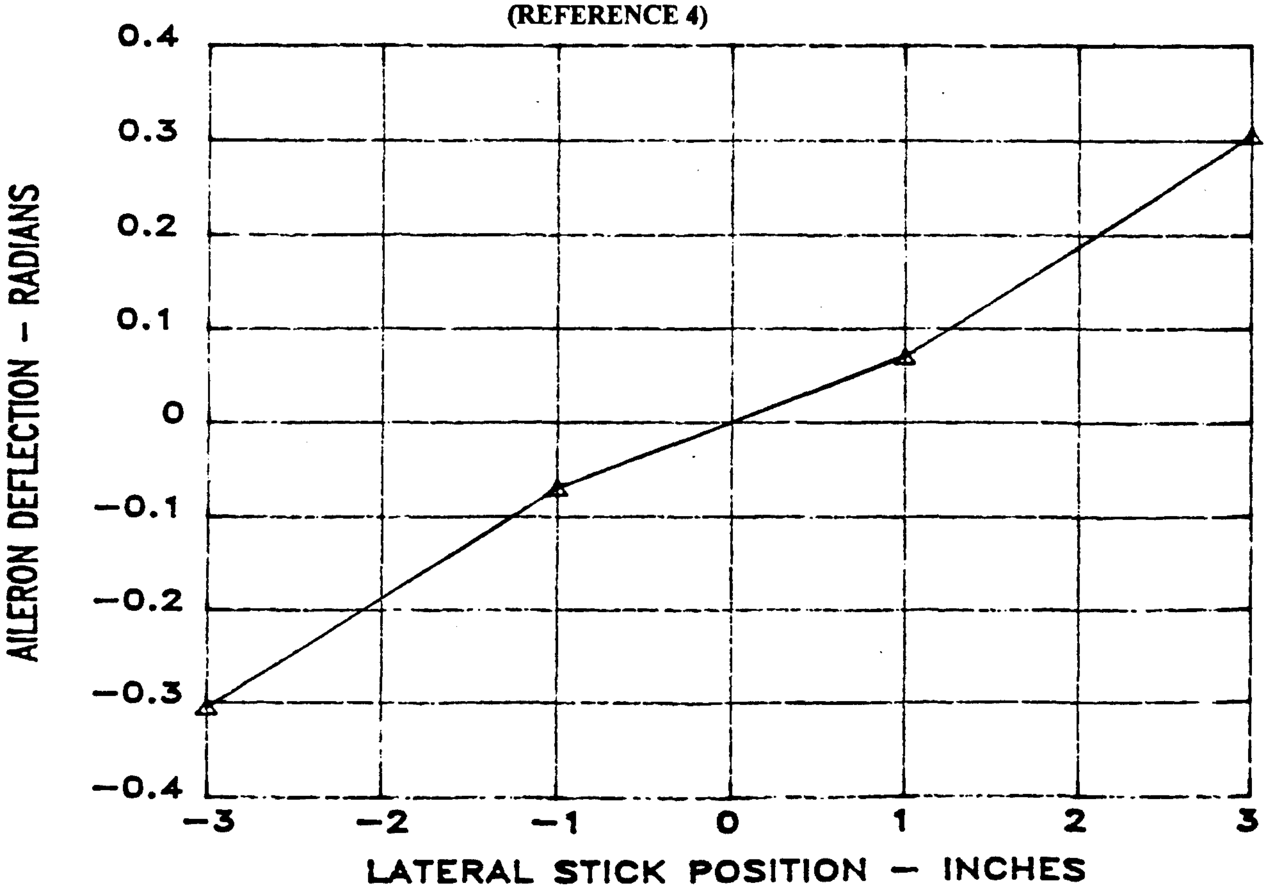
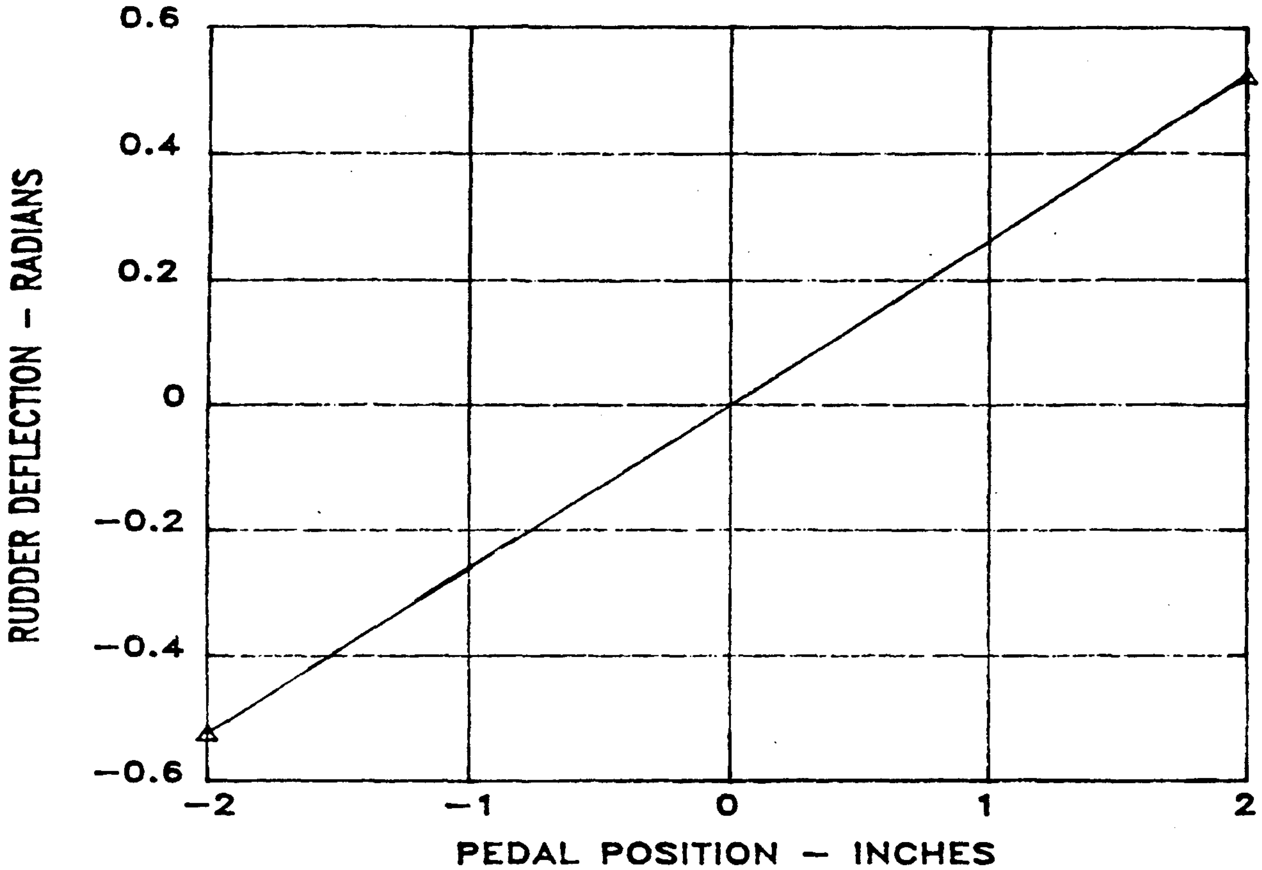


FIGURE B6. RUDDER GEARING CURVE
(REFERENCE 4)



APPENDIX C

NONLINEAR DATA PLOTS

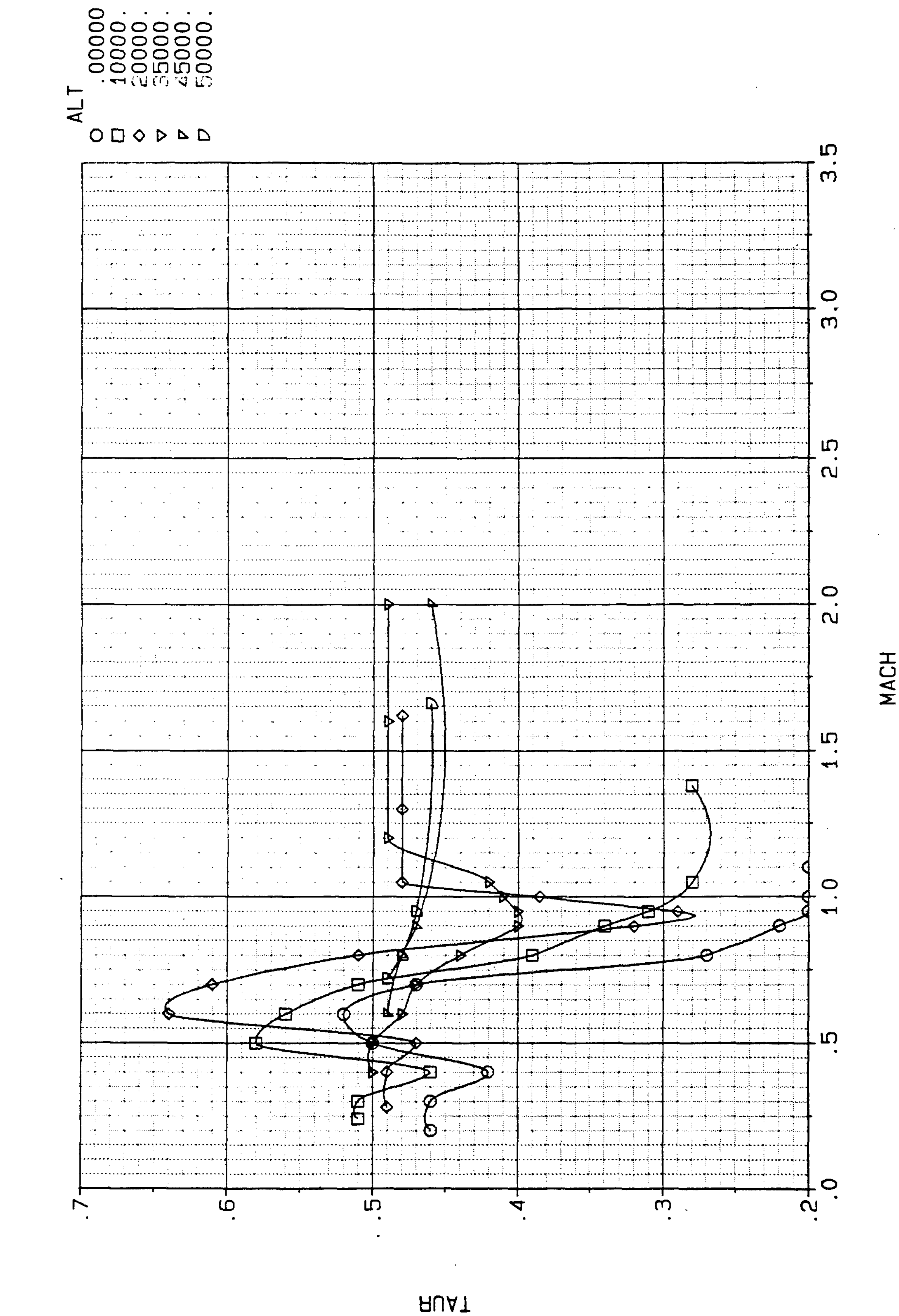


FIGURE C1. ROLL MODE TIME CONSTANT (SEC)

FIGURE C2. DUTCH ROLL FREQUENCY (RAD/SEC)

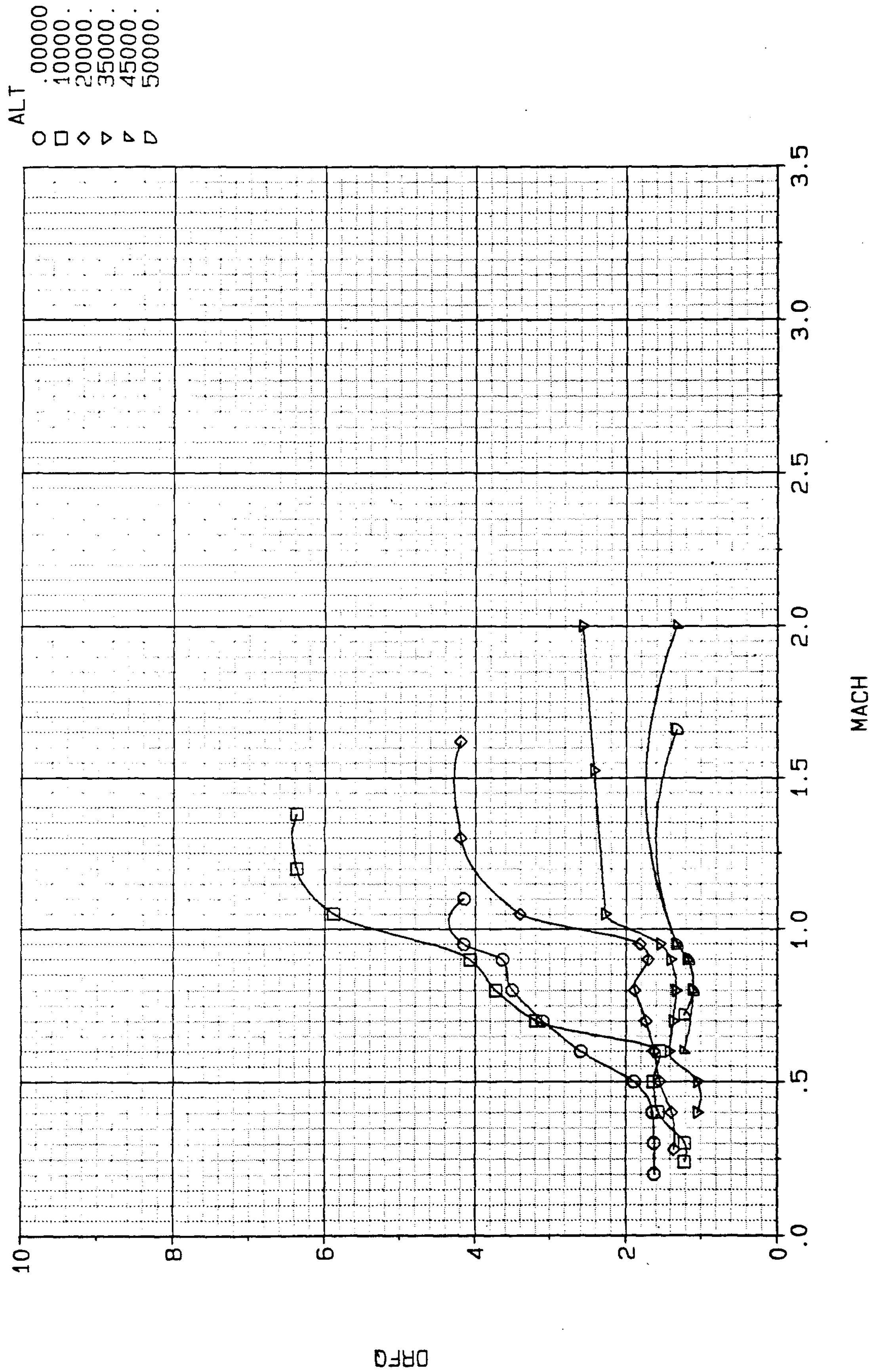


FIGURE C3. DUTCH ROLL DAMPING

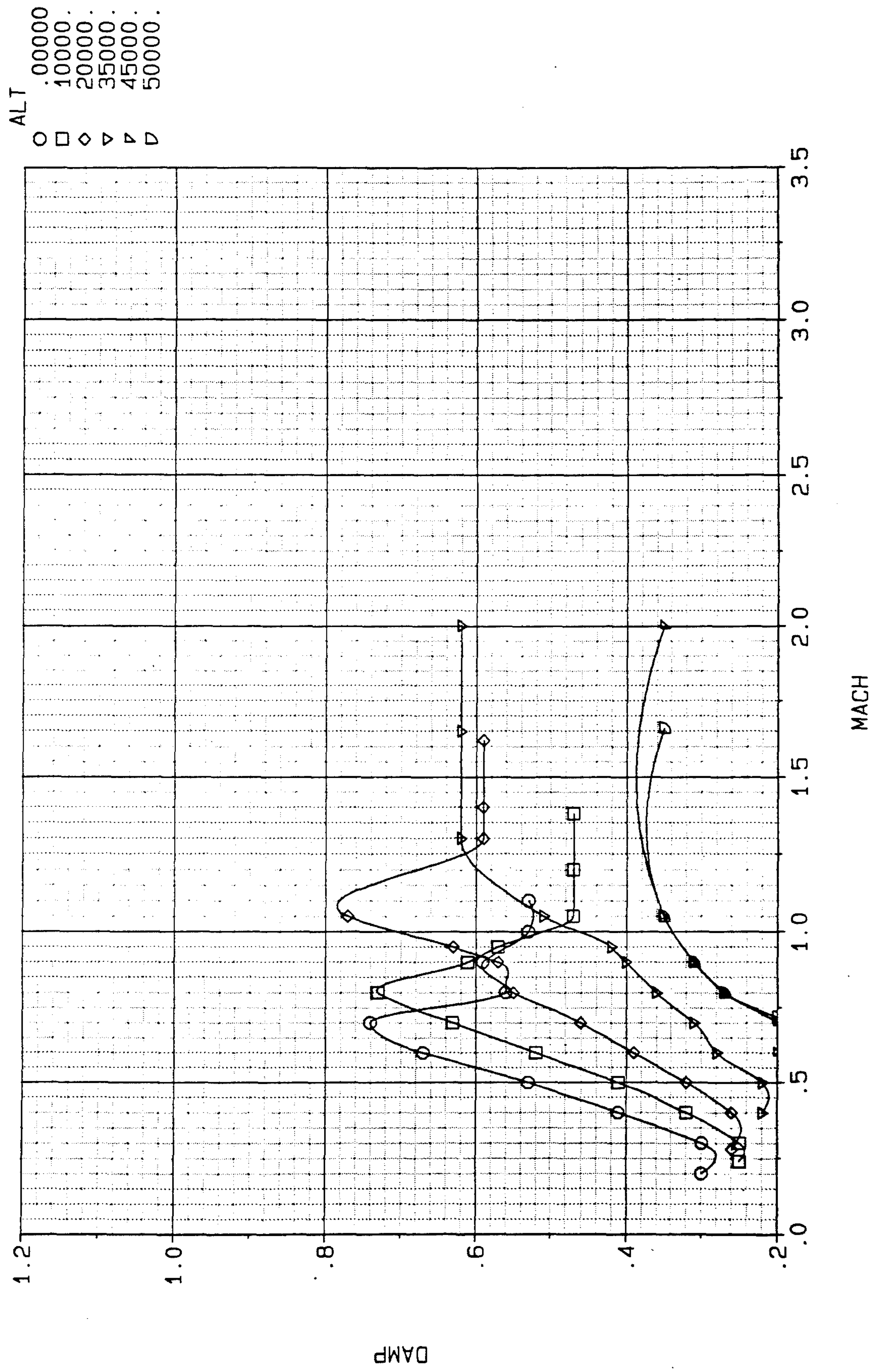


FIGURE C4. P STEADY-STATE MAX (DEG/SEC)

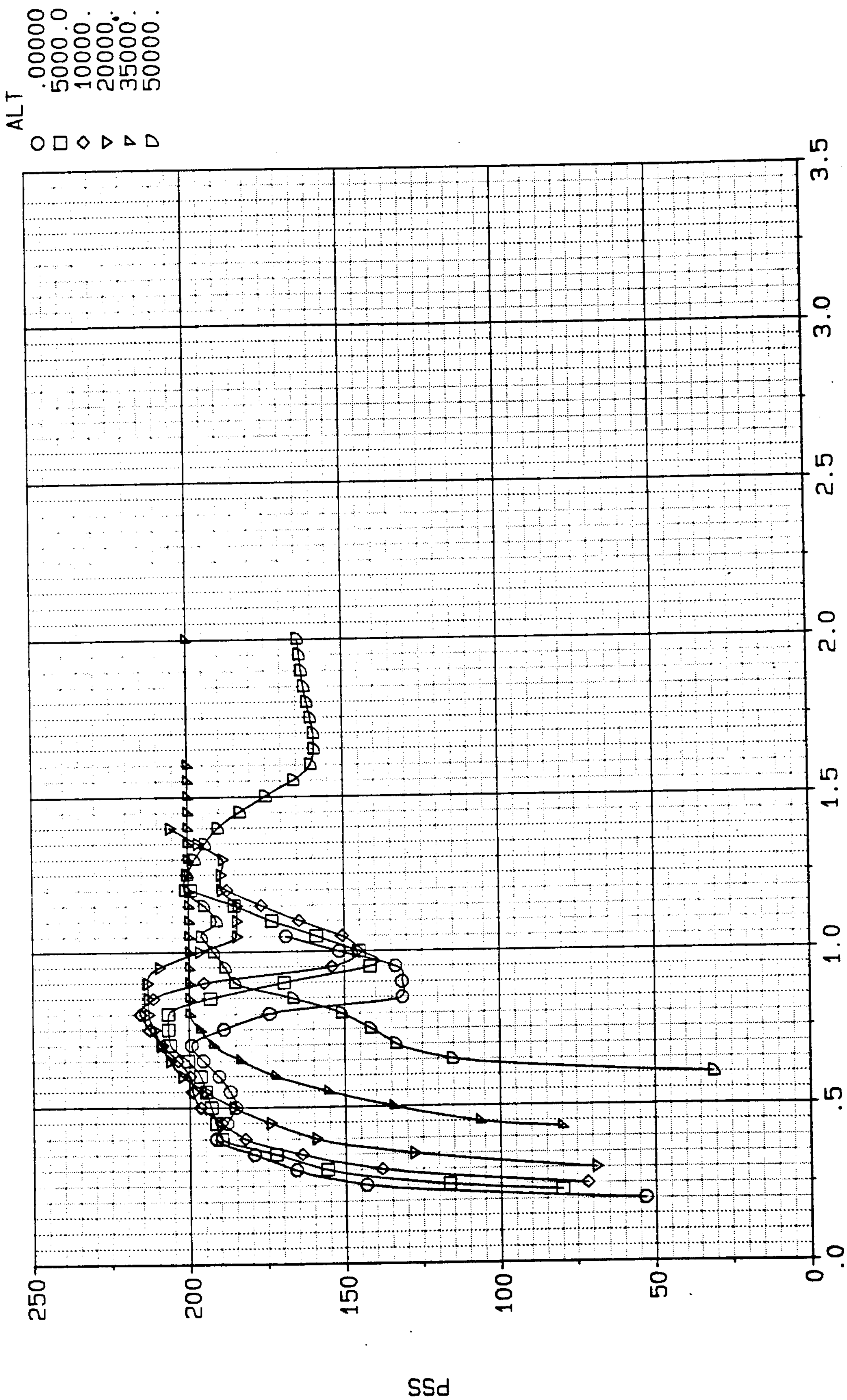


FIGURE C5 VARIATION OF SIDE FORCE WITH RUDDER DEFL.
(1/RAD)

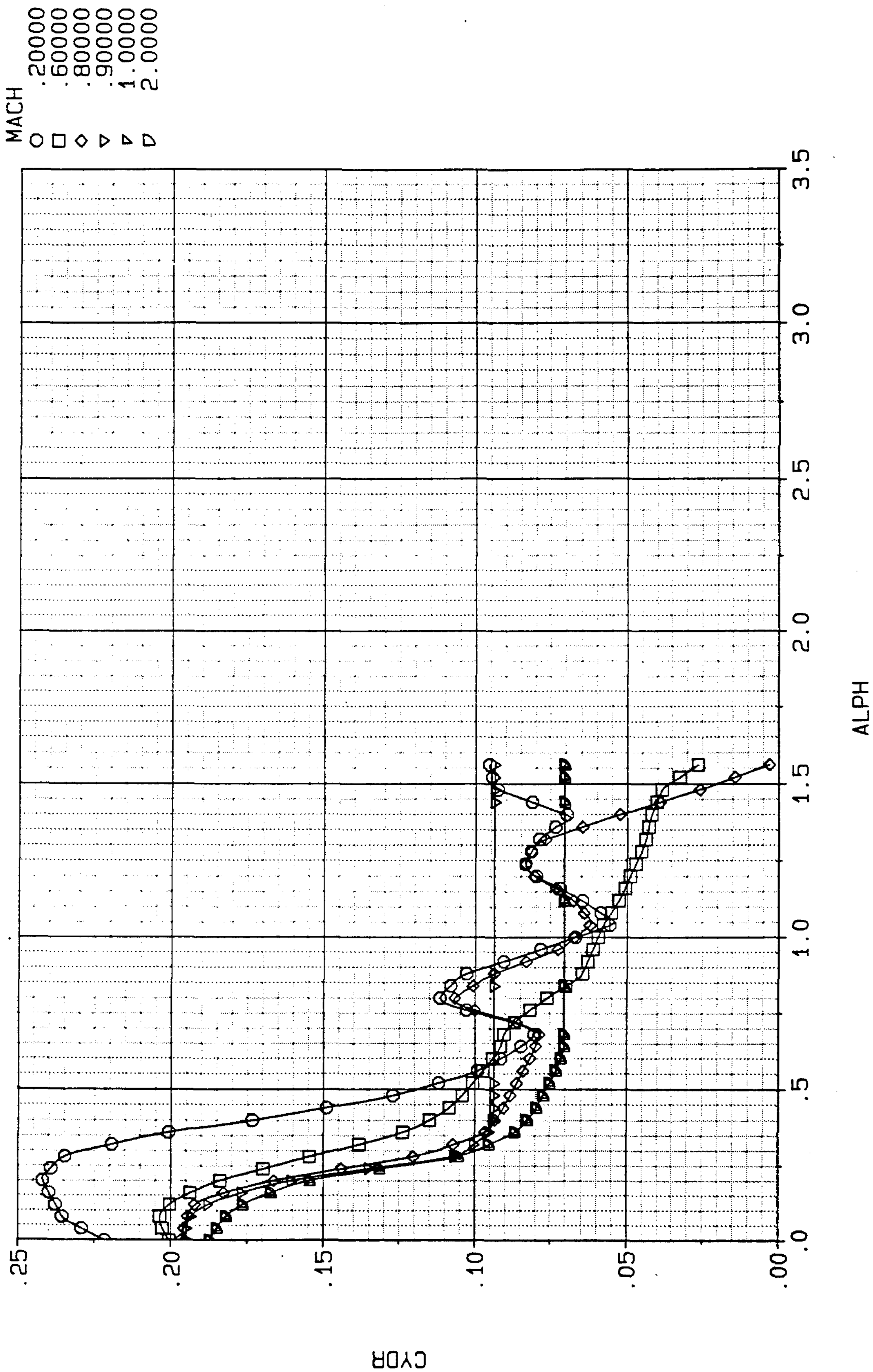


FIGURE C6. VARIATIOIN OF ROLLING MOMENT WITH RUDDER DEFL. (1/RAD)

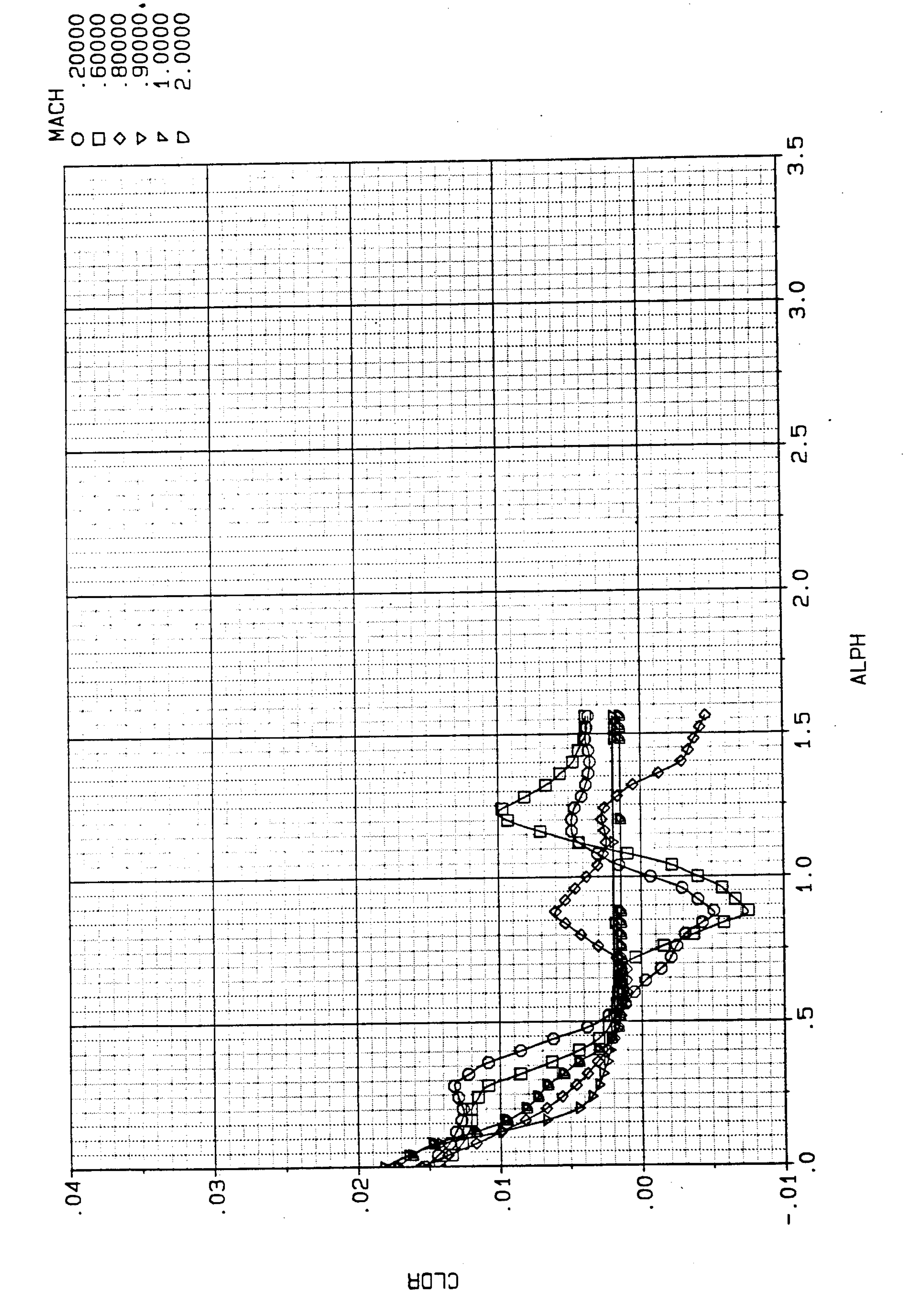


FIGURE C7. VARIATION OF YAWING MOMENT WITH RUDDER DEFL. (1/RAD)

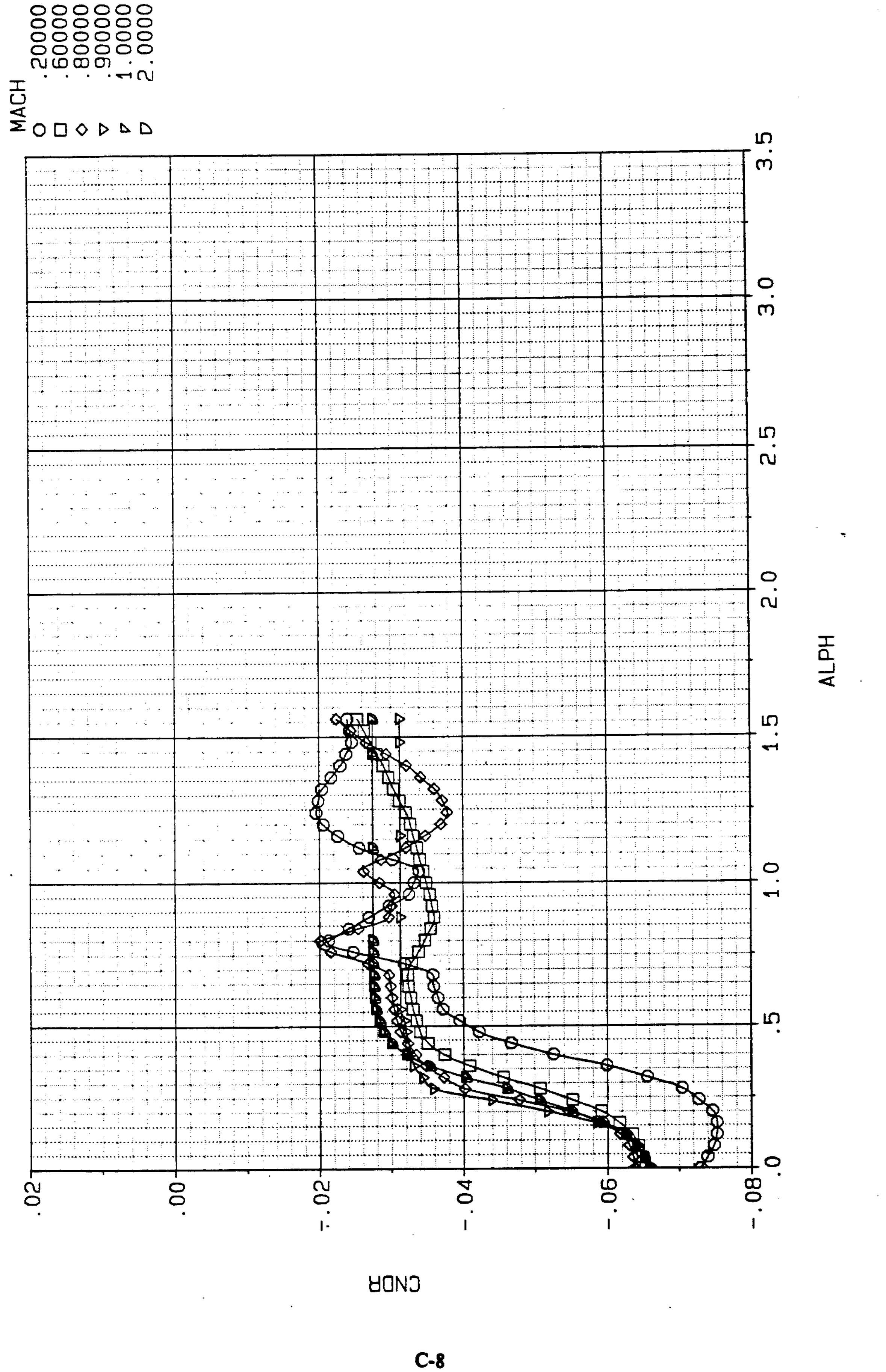


FIGURE C8. VARIATION OF YAWING MOMENT WITH YAW RATE
(1/RAD)

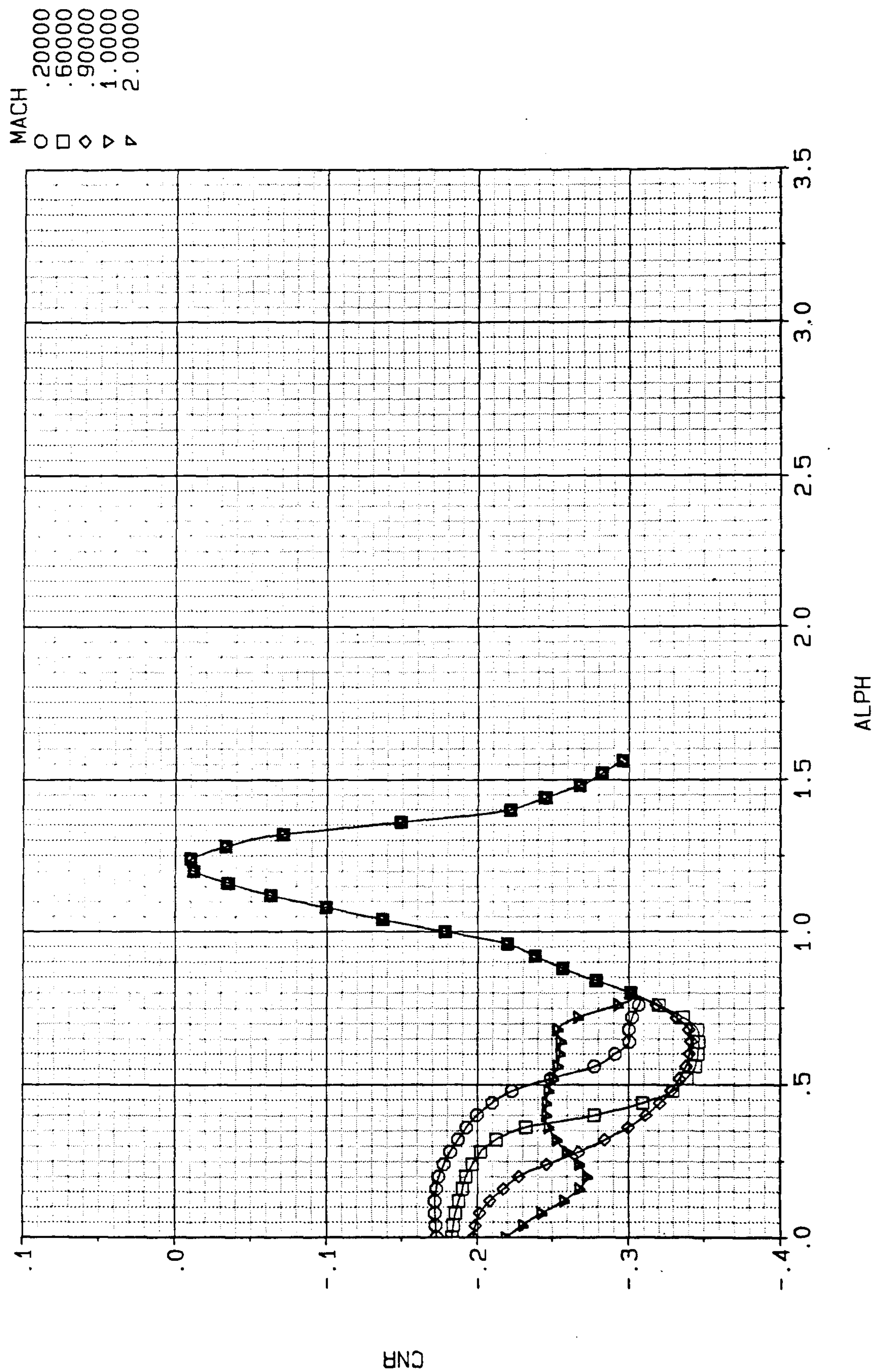


FIGURE C9. VARIATION OF ROLLING MOMENT WITH YAW RATE
(1/RAD)

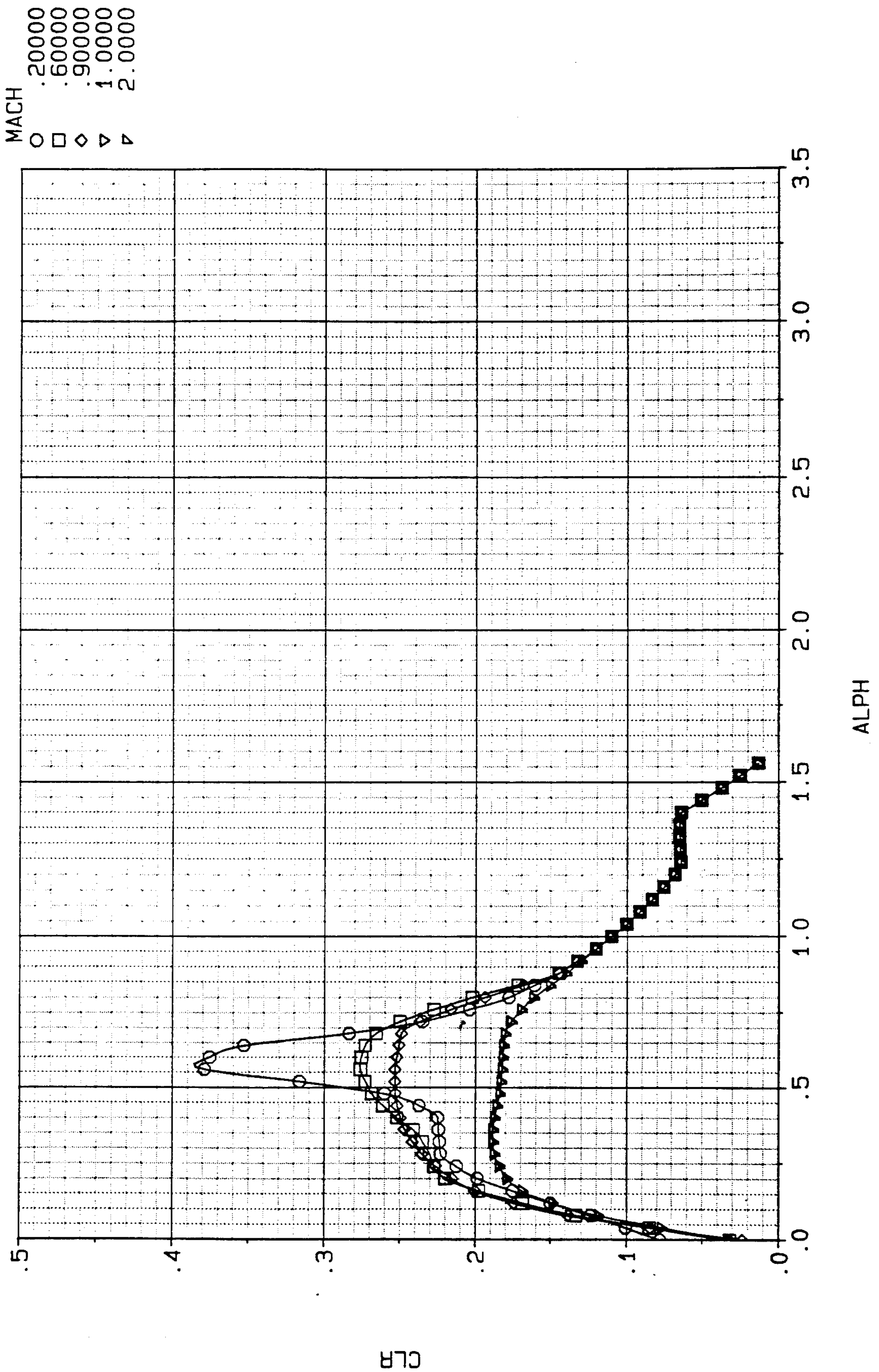


FIGURE C10. VARIATION OF SIDE FORCE WITH AILERON DEFL.
(1/RAD)

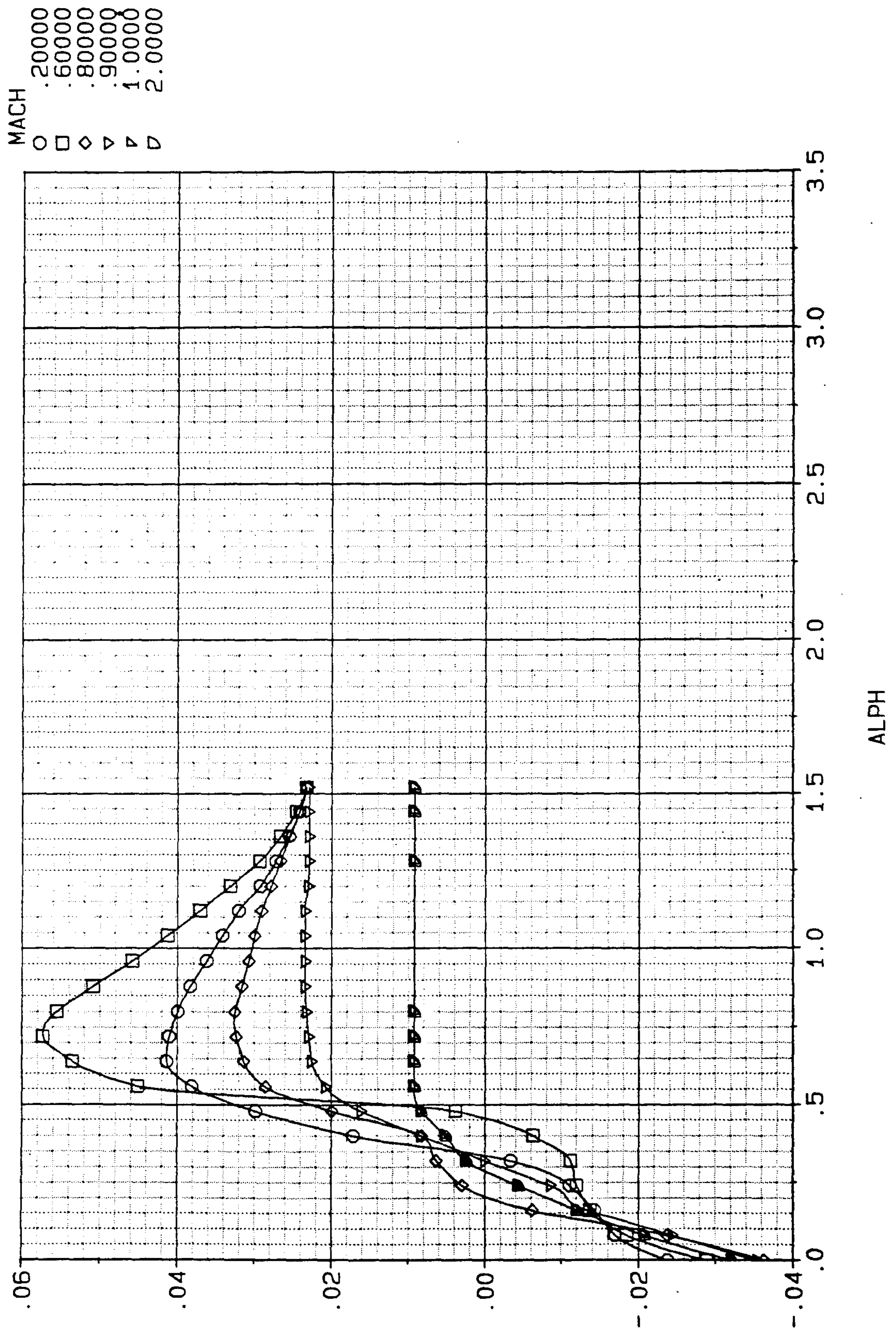
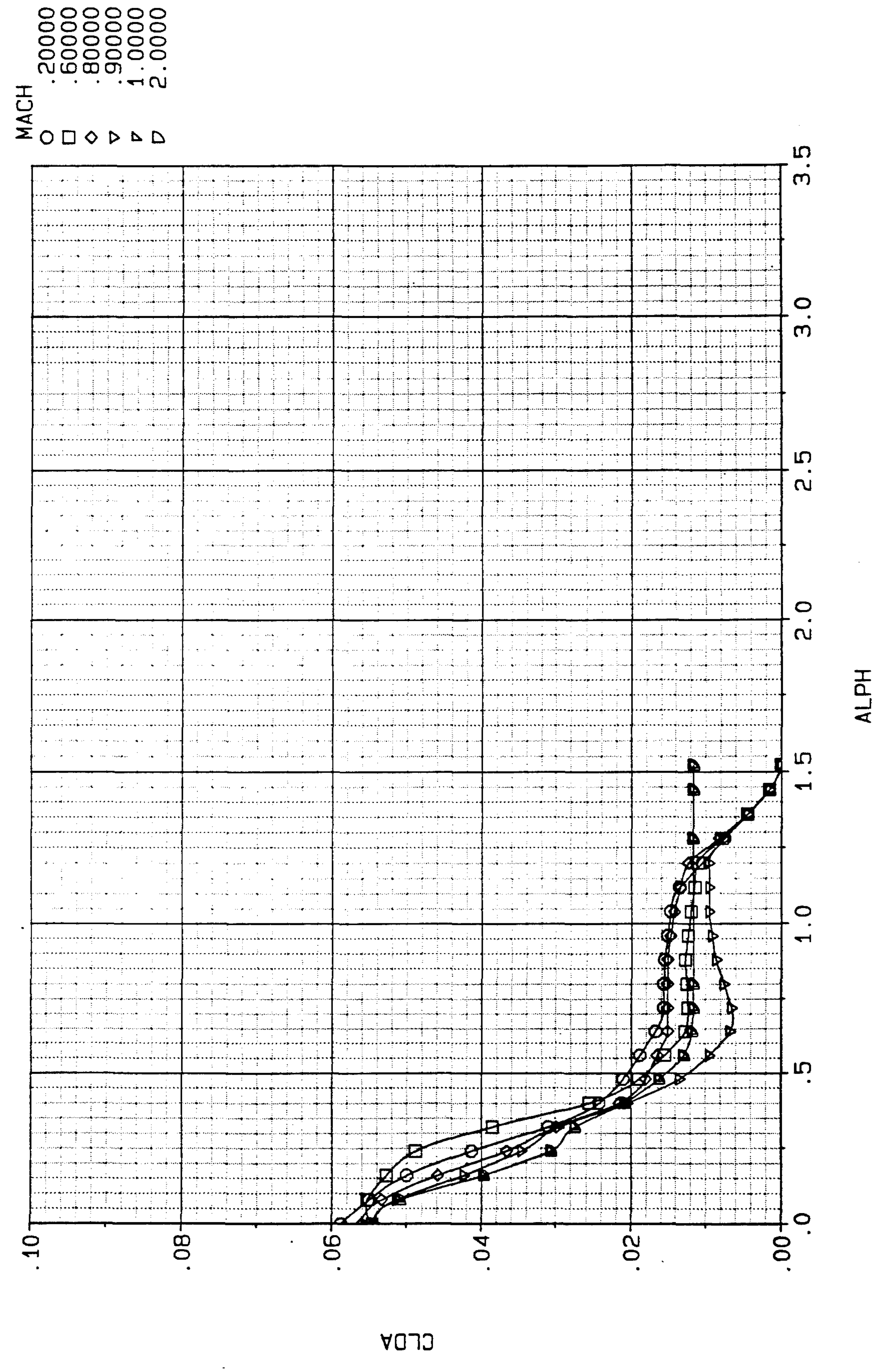


FIGURE C11. VARIATION OF ROLLING MOMENT WITH AILERON DEFL. (1/RAD)



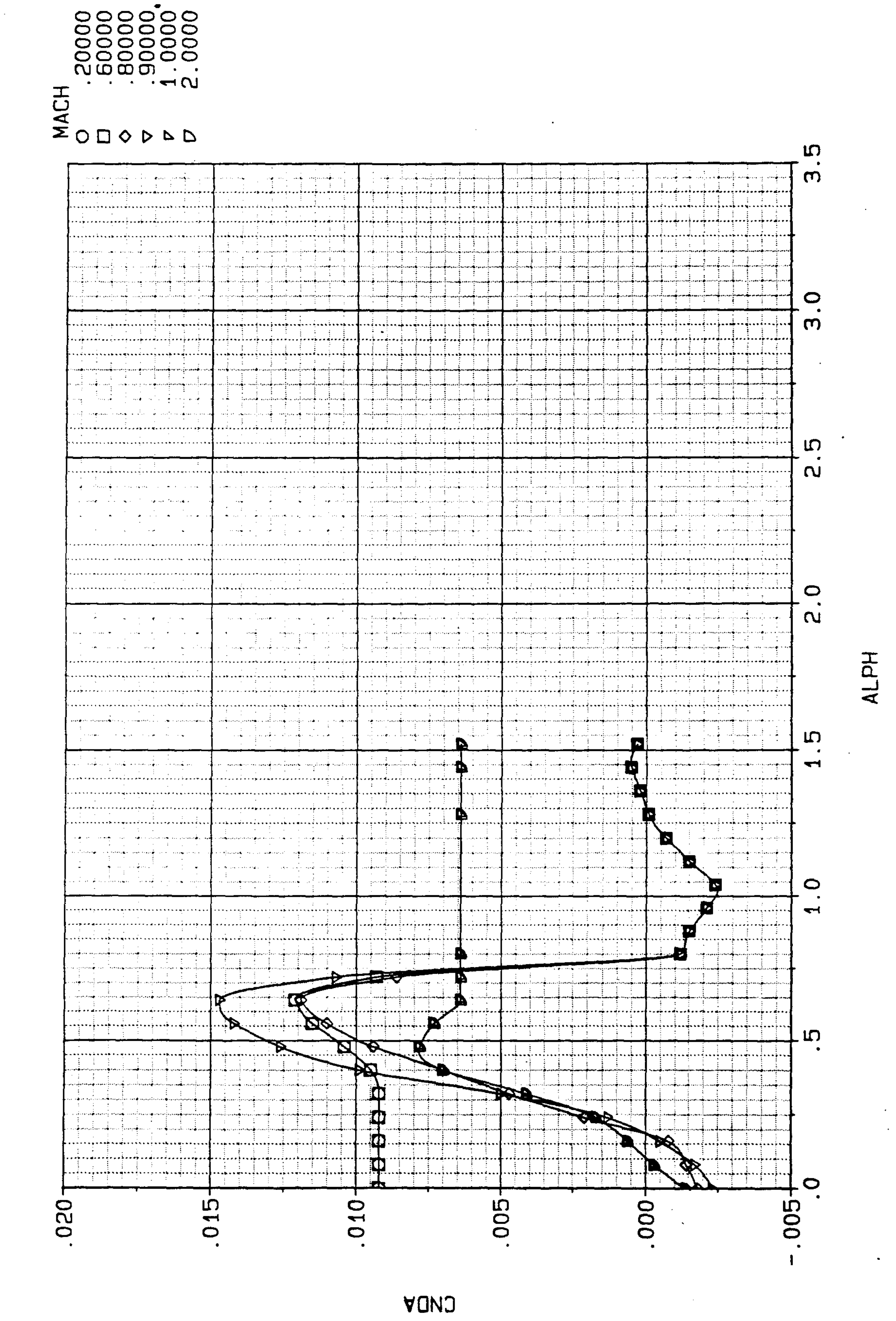


FIGURE C12. VARIATION OF YAWING MOMENT WITH AILERON DEFL. (1/RAD)

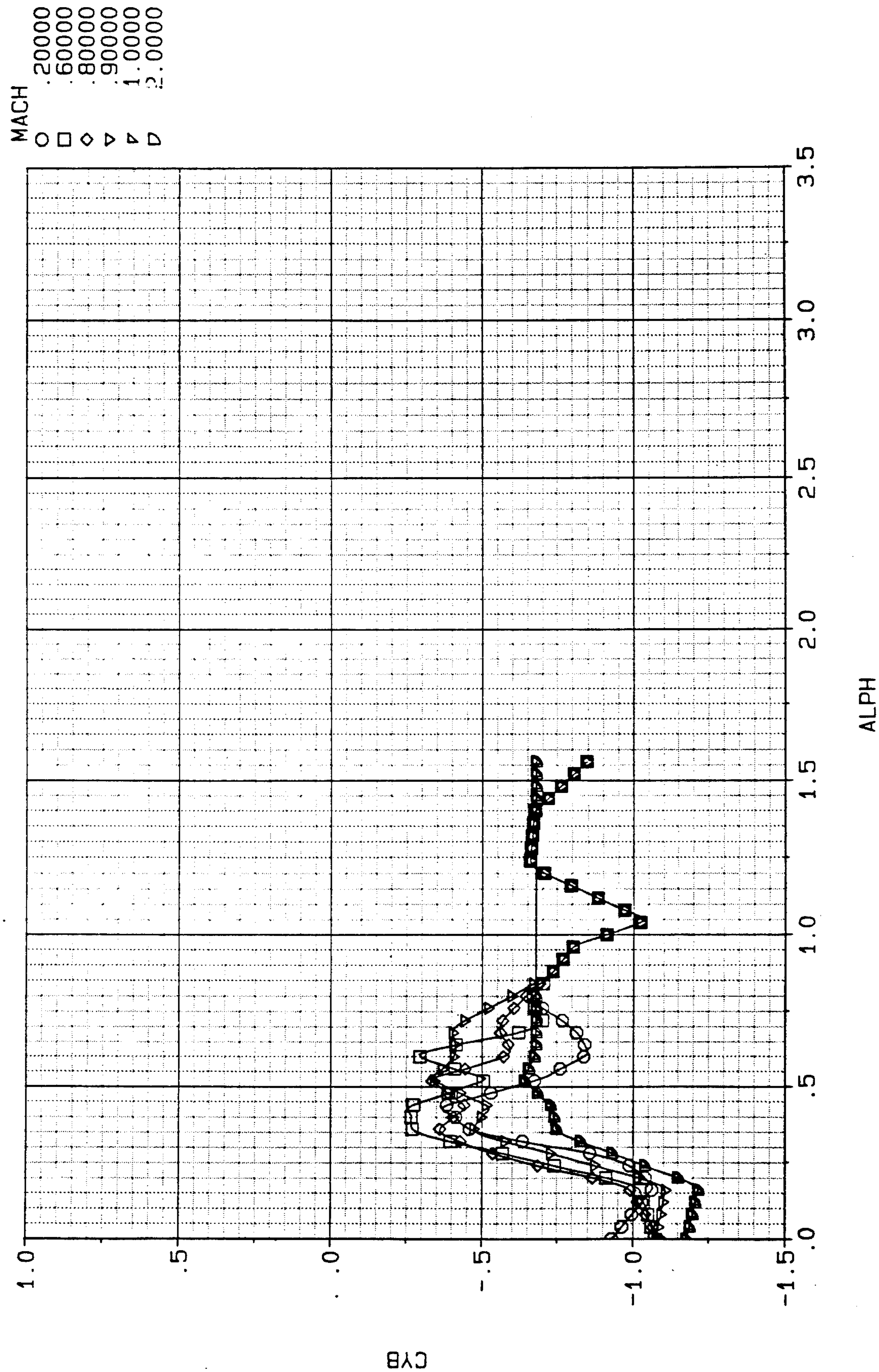


FIGURE C13. VARIATION OF SIDEFORCE WITH SIDESLIP (1/RAD)

FIGURE C14. VARIATION OF YAWING MOMENT WITH SIDESLIP (1/RAD)

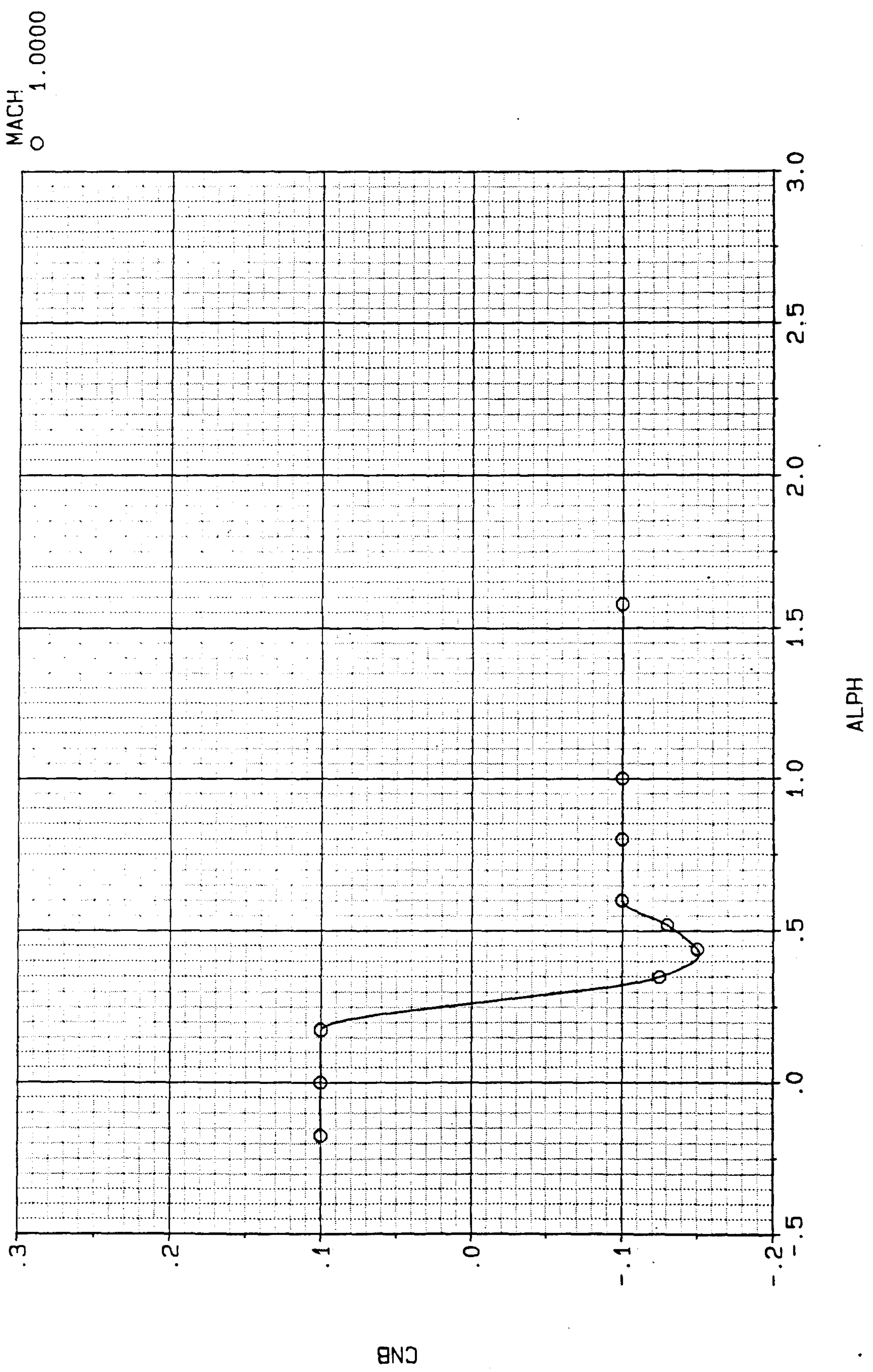


FIGURE C15. VARIATION OF ROLLING MOMENT WITH SIDESLIP (1/RAD)

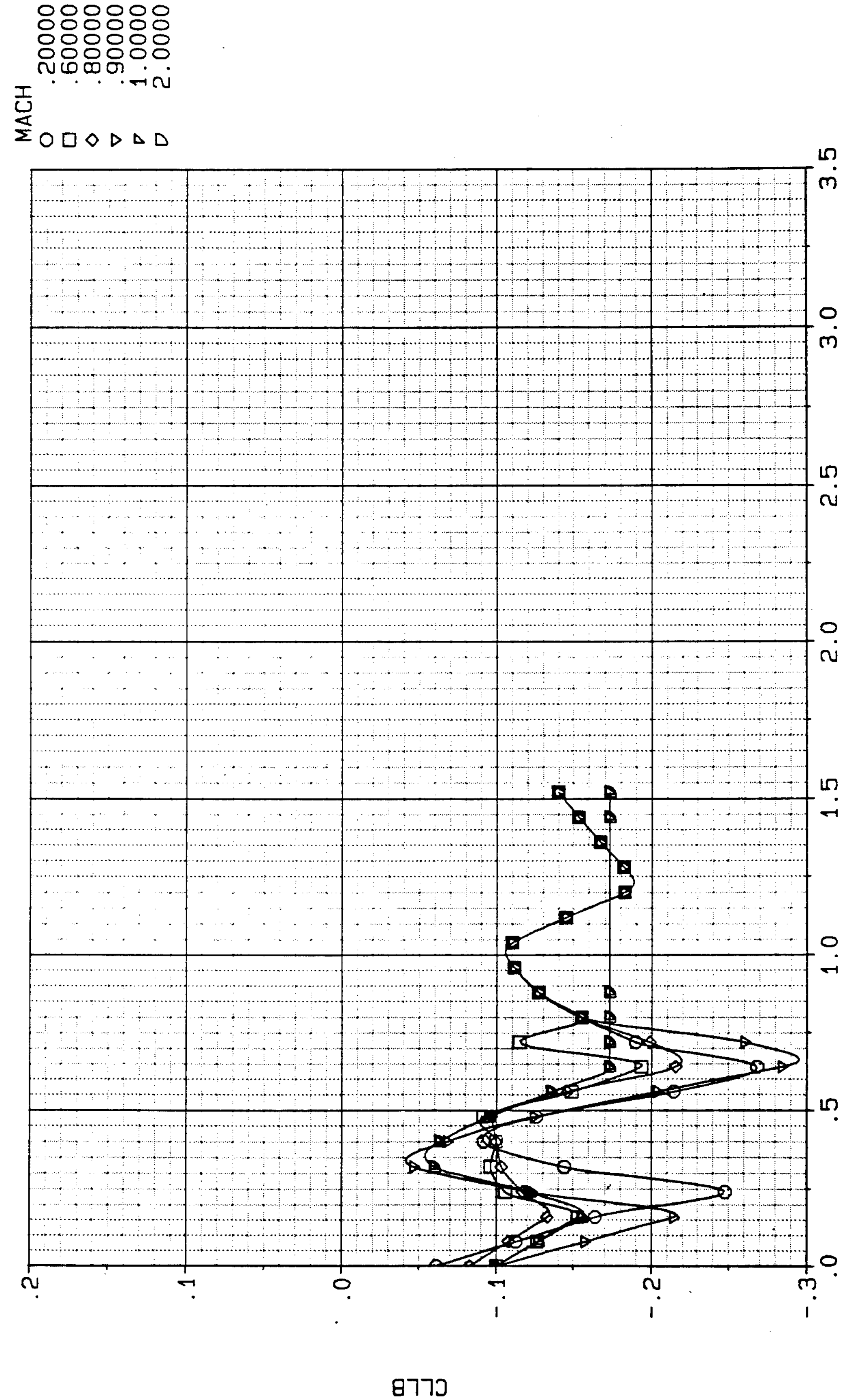
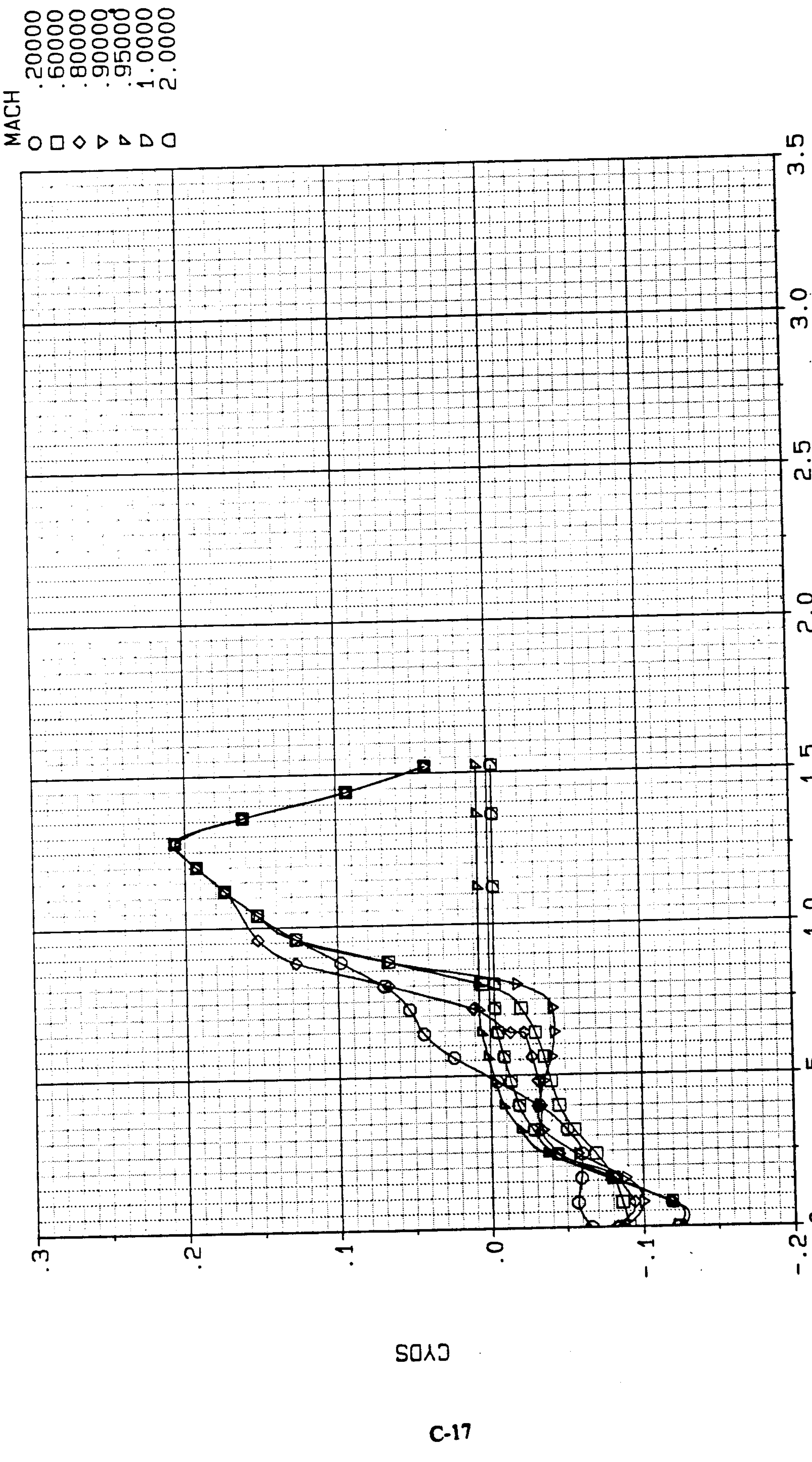


FIGURE C16. VARIATION OF SIDE FORCE WITH STABILIATOR DEFL. (1/RAD)



1:39:23 30 JAN 1994 FROM FILE b: f181d.tig

FIGURE C17. VARIATION OF ROLLING MOMENT WITH STABILATOR DEFL. (1/RAD)

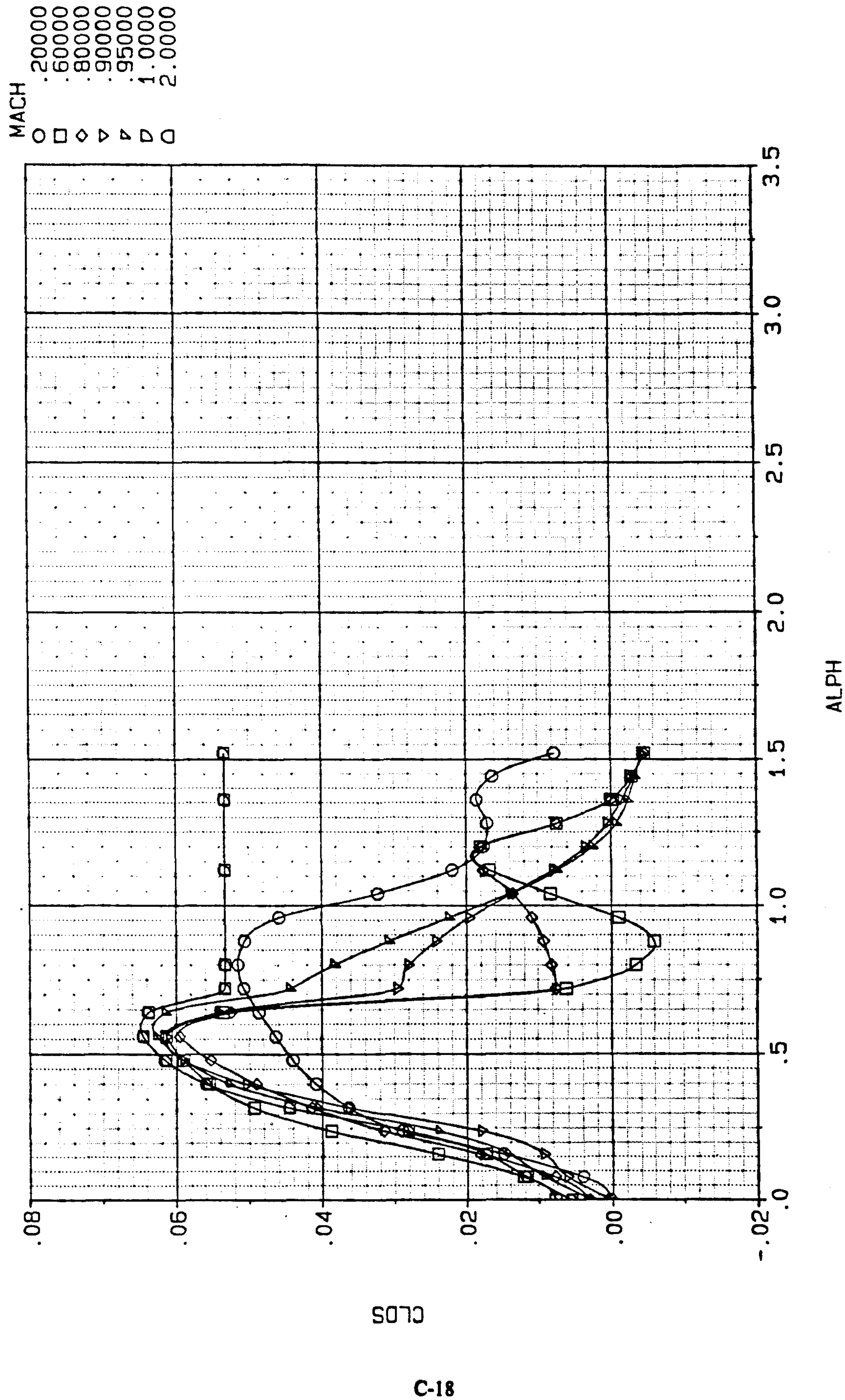
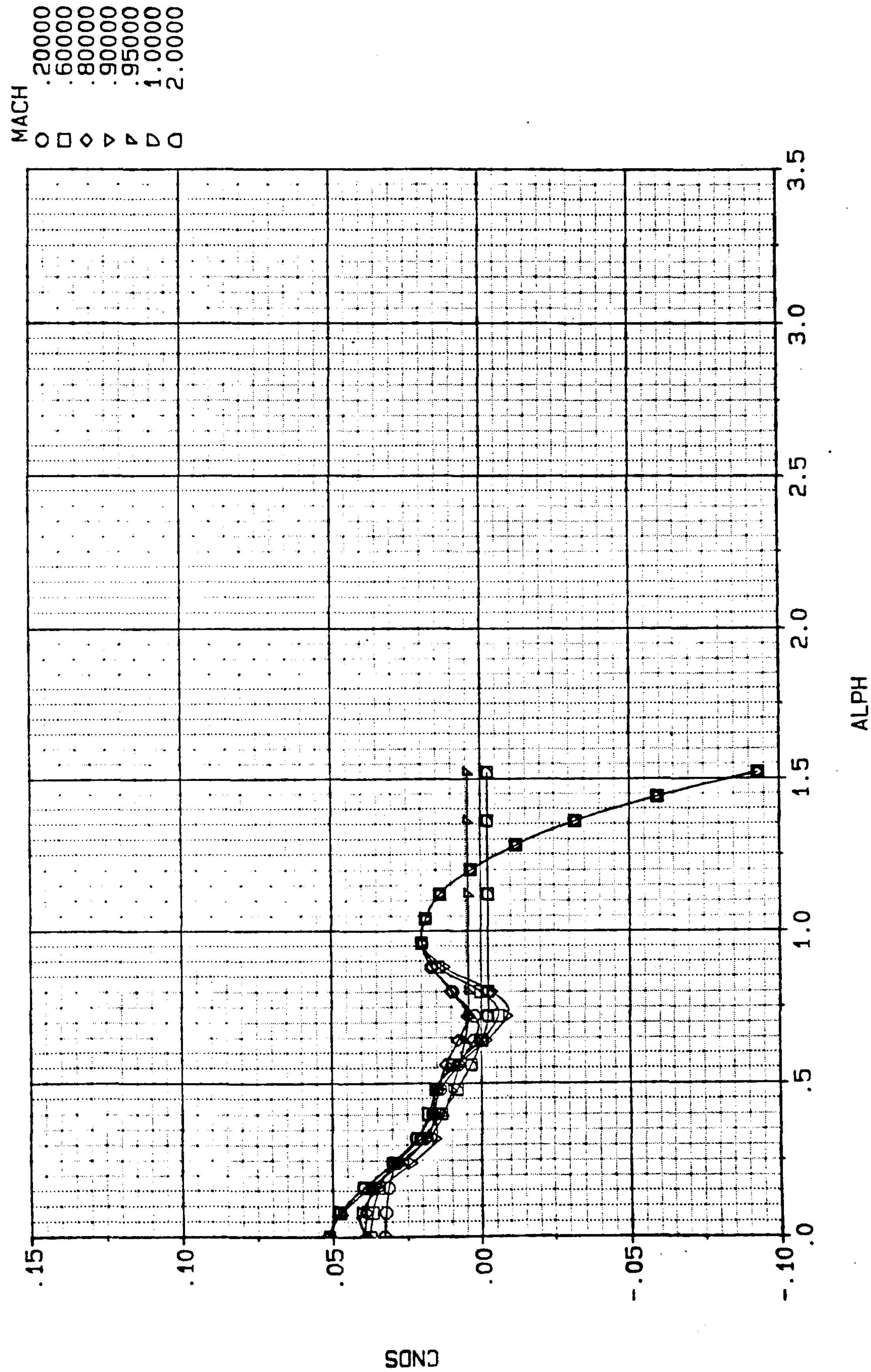


FIGURE C18. VARIATION OF YAWING MOMENT WITH STABILIATOR DEFL. (1/RAD)



APPENDIX D

SAMPLE INPUT FILE

TABLE D1. SAMPLE FLIGHT CONDITIONS

CASE NUMBER	MACH	ALTITUDE (FT)	ANGLE OF ATTACK (RAD)
1	.2	1000	.1414
2	.6	35000	.1093
3	.9	10000	.0171
4	0	35000	.05

Note: Case 4 is not a valid flight condition.

FIGURE D1. INPUT FILE FORMAT

Title
$Mach_1, Altitude_1 (feet), Angle\text{-}Of\text{-}Attack_1$ *(radians)*
$Mach_2, Altitude_2 (feet), Angle\text{-}Of\text{-}Attack_2$ *(radians)*
.
.
.
$Mach_n, Altitude_n (feet), Angle\text{-}Of\text{-}Attack_n$ *(radians)*

where each subscript refers to each flight condition

FIGURE D2. SAMPLE INPUT FILE

```
TEST FILE FOR F-18 TRANSFER FUNCTION PROGRAM 3/16/94
.2,1000,.1414
.6,35000,.1093
.9,10000,.0171
0,35000,.05
```

APPENDIX E

SAMPLE OUTPUT FILE

TEST FILE FOR F-18 TRANSFER FUNCTION PROGRAM 3/16/94

Case Number 1
mach = .200 alt = 1000.0 alpha(rad) = .141

Denominator to Lateral-Directional Transfer Functions.
Coefficients are in descending order of s.

1.000000 1.719688 3.037692 1.144893 .000000

p to lateral stick force transfer function numerator
13.966980 17.499701 34.259322 .000000

phi to lateral stick force transfer function numerator
13.966980 17.499701 34.259322

beta to lateral stick force transfer function numerator
.000000 .000000

r to lateral stick force transfer function numerator
.327676 .001629

aycg to lateral stick force transfer function numerator
-7.843049 -8.566533 -19.231792

p to pedal force transfer function numerator
-.013788 -.000792 .111820 .000000

phi to pedal force transfer function numerator
-.013788 -.000792 .111820

beta to pedal force transfer function numerator
-.000385 -.068454

r to pedal force transfer function numerator
.068420 .000526

aycg to pedal force transfer function numerator
.006261 .000313 -.060769

Case Number 2
mach = .600 alt = 35000.0 alpha(rad) = .109

Denominator to Lateral-Directional Transfer Functions.
Coefficients are in descending order of s.

1.000000 1.616000 2.561680 .967872 .000000

p to lateral stick force transfer function numerator
29.709662 33.750175 59.906559 .000000

phi to lateral stick force transfer function numerator
29.709662 33.750175 59.906559

beta to lateral stick force transfer function numerator
.000000 .000000

r to lateral stick force transfer function numerator
.210279 .003787

aycg to lateral stick force transfer function numerator
-16.683230 -16.822641 -33.601716

p to pedal force transfer function numerator
-.001718 .000252 .306057 .000000

phi to pedal force transfer function numerator
-.001718 .000252 .306057

beta to pedal force transfer function numerator
-.000113 -.072688

r to pedal force transfer function numerator
.072675 .000538

aycg to pedal force transfer function numerator
-.000177 -.000277 -.166413

Case Number 3
mach = .900 alt = 10000.0 alpha(rad) = .017

Denominator to Lateral-Directional Transfer Functions.
Coefficients are in descending order of s.

1.000000 5.293200 18.167690 5.604424 .000000

p to lateral stick force transfer function numerator
44.700194 221.409001 736.820090 .000000

phi to lateral stick force transfer function numerator
44.700194 221.409001 736.820090

beta to lateral stick force transfer function numerator
.000000 .000000

r to lateral stick force transfer function numerator
2.462298 .047704

aycg to lateral stick force transfer function numerator
-25.101046 -82.655994 -412.948207

p to pedal force transfer function numerator
-.050856 -.014647 3.596983 .000000

phi to pedal force transfer function numerator
-.050856 -.014647 3.596983

beta to pedal force transfer function numerator

-.000668 -.266152

r to pedal force transfer function numerator
.265872 .001211

aycg to pedal force transfer function numerator
.017259 .003494 -1.999366

Case Number 4
mach = .000 alt = 35000.0 alpha(rad) = .050
Trim flight conditions outside of permissible flight envelope

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